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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD CONFERENCE PROCEEDINGS 513

Piloted Simulation Effectiveness

(L'Efficacité de la Simulation Pilotée)

Copies of papers presented at the Flight Mechanics Panel Symposium held in Brussels, Belgium from 14th–17th October 1991.

NORTH ATLANTIC TREATY ORGANIZATION

Published February 1992

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

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According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

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Preface

The ability of piloted simulators to represent military and civil aviation operational tasks with ever-increasing levels of fidelity is leading to a steady growth in their use for all areas of aviation from new concept studies, through support for development and flight clearance, to training air-crew for complex missions. In all applications of simulation the essential question is "What level of confidence do I have in this simulator's capabilities to represent the tasks I am going to perform?" This Symposium has brought together papers presenting a variety of experience of the effectiveness of simulation for many of the key areas of applications.

Sessions focused on:

- the use of simulation in aircraft development programmes, including some of the issues raised by the use of simulation as part of flight clearance activities;
- the use of simulation in developing piloting skills;
- the use and potential of simulation in full mission training for military rôles;
- the effectiveness of simulation for a variety of research tasks, including developing flying qualities criteria and exploring new concepts.

The aim was to give attendees a view of the many contributions made by flight simulators, a change to update their knowledge of the effectiveness of simulation for a wide range of tasks, and a glimpse of the future potential of simulation.

Préface

La capacité des simulateurs pilotés pour représenter les tâches opérationnelles de l'aviation civile et militaire à des niveaux de fidélité de plus en plus élevés explique leur emploi de plus en plus courant dans tous les domaines de l'aviation, des études de concept à l'entrainement des équipages pour des missions complexes, en passant par le soutien au développement et à l'autorisation de vol.

La question essentielle qui se pose dans toutes les applications des techniques de simulation est la suivante: «A quel point ai-je confiance en la capacité de ce simulateur pour représenter les tâches que je vais exécuter?» Ce symposium a réuni des communications qui présentent une diversité d'expériences en ce qui concerne l'efficacité de la simulation dans différents domaines clés d'application.

Les séances ont porté sur les sujets suivants:

- l'emploi de la simulation dans les programmes de développement avion, y compris certaines questions soulevées par l'emploi de la simulation dans le cadre des activités d'autorisation de vol;
- l'emploi de la simulation pour l'entraînement au pilotage;
- l'emploi et le potentiel de la simulation pour l'entraînement à la mission militaire à grandeur nature;
- l'efficacité de la simulation pour diverses tâches de recherche, y compris le développement des critères des qualités de vol et l'examen de concepts nouveaux

L'objet du symposium était d'offrir aux participants un panorama des contributions faites par les simulateurs de vol, de les présenter l'état des connaissances actuelles en ce qui concerne l'efficacité de la simulation pour une large gamme de tâches, et de leur donner un aperçu des possibilités futures.

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Le Panel du Mécanique du Vol tient à remercier les Autorités Nationales de La Belgique pour leur invitation à tenir cette réunion à Bruxelles ainsi que des installations et du personnel mis à sa disposition.

Contents

OPPORTUNITIES FOR FLIGHT SIMULATION TO IMPROVE OPERATIONAL EFFECTIVENESS

by

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Abstract

This keynote address gives an overview over the opportunities of piloted simulation for the development of aircraft and for the training of aircrews to operate the aircraft.

Based on the military flight mission requirements some critical issues of peacetime military operations in Europe are discussed and the resulting opportunities for application of flight simulation in development and training are presented.

The address concludes on recommendations for piloted simulation.

1. Introduction

Mr. chairman, ladies and gentlemen!

It is a great pleasure and honour for me to be invited to present a keynote address at this AGARD Symposium. Particularly so because my association with AGARD as a National Delegate has proved to be very inspiring. Also, representing a nation which is located right in the middle of a densely populated Europe and being challenged by the European dilemma of low-level flight training I would like to stress that this symposium on Piloted Simulation Effectiveness is highly relevant and of utmost importance not only to Germany but to the NATO community as a whole.

My presentation, therefore, will include - as you can see from the viewgraph (Figure 1) - a review of selected military mission requirements and related critical issues concerning military flight operations in Europe.

In recent years important advances have been made in the field of simulator technology for research, development and training purposes.

Consequently, I will address opportunities provided by piloted simulation for flight vehicle development and verification and its significance for advanced aircrew training.

I will conclude with certain expectations and recommendations which I hope will stimulate the researchers, designers and operators present in their efforts to further improve piloted simulation effectiveness.

Piloted simulation serves two primary purposes. One is to support the aircraft development and related research, and the other is to train aircrews to operate the aircraft. Even though these two application areas are quite different, the requirements, designs, and performance may be very similar in many aspects.

In my address I am concerned with both types of simulation systems, i.e. the development simulator and the training simulator. Both have become indispensable tools for fulfilling the greater need for real-time man-in-the-loop simulation of more complex weapon systems.

The use of simulation techniques for aircrew and system operator training dates back more than sixty years when a device such as the Link Trainer was developed and later successfully used to train thousands of pilots during the Second World War. The viewgraph (Figure 2) shows an early Link Trainer with flight path recorder. *"The Link Trainer has been found helpful in reducing flight time and in instructing pilots in new methods of orientation and maintaining their instrument flying efficiency"*. This statement was given by the American author D. W. Tomlinson, a former US Marine pilot, who presented a paper on this subject at the Annual Meeting of the German Lilienthal Society on 13th October 1938 in Berlin [1].

Future air warfare will place enormous demands on both situational awareness outside the cockpit and system or sensor interpretation inside the cockpit. On the viewgraph (Figure 3) you can see that the air vehicle part is beeing continuously improved by the increased integration of systems like multifunction displays, controls and avionics needed to support wide ranging mission requirements. Development simulation will help to extend these capabilities.

This kind of increased system sophistication has confronted their operators with increasing psychological and physiological demands. While it is generally appreciated that the pilot's psychomotoric and cognitive skills, which means his ability to acquire, process and make effective control decisions, are key contributors to military operational effectiveness, there are significant difficulties in improving the match between new cockpit and system technologies and pilot capabilities.

The most important means of improving the man-machine interface is the increased utilization of piloted simulators for air vehicle development as well as for pilot qualification and training. The final answer to the question of how to improve military opera-

tional effectiveness in future air warfare will heavily depend on the amount of automation that a pilot needs for effective decision-making with an acceptable workload.

In recognition of the important contributions the AGARD Flight Mechanics Panel (FMP) has made to the simulation community of the NATO member nations (see Table 1), it is worthwhile to recall that more than thirty technical documents have been produced since 1956 in the form of AGARD Reports, Advisory Reports, AGARDographs and Conference Proceedings, which are now standard reference material. Various symposia on this topic have been organized, the last being in Cambridge, England, in late 1985.

As you can see on the viewgraph (Figure 4) AGARD has played an equally important role in the development of piloted simulation through its technical Working Groups, where advances in flight simulation technology for improved fidelity and utility have been identified, evaluated and documented.

I am looking forward to hearing more in the near future about the results achieved by Working Group 16 on *Validation of Simulation Systems for Aircraft Acceptance Testing* and Working Group 20 on *Piloted Simulation in Low Altitude High Speed Mission Rehearsal.*

Important contributions to piloted simulation techniques have also been made by the Aerospace Medical Panel (AMP), the Guidance and Control Panel (GCP) and the Aerospace Application Sub-Committee (AASC). The viewgraph (Figure 5) clearly demonstrates the interdisciplinary nature of the subject and the need to bring together individuals from different scientific, technical and operational backgrounds in order to improve the understanding of the man-machine interface of piloted simulators.

2. Military Flight Mission Requirements

Ladies and gentlemen, the NATO armed forces training and simulation programmes are closely coupled to current and future Military Flight Mission Requirements. The current requirements of the German forces are shown on the viewgraph (Figure 6). They are more or less representative of the Allied NATO forces in Europe.

Changing global political realities like the collapse of the Warsaw Pact have contributed to uncertainties about the future role of the NATO armed forces. These uncertainties have also manifested themselves in cuts in budgets.

In contrast to this, lessons have to be learned from the Gulf Crisis, yielding a new requirement for multinational flexible and mobile military task forces probably under the political umbrella of the United Nations.

From this, it can be concluded that air weapon systems of the future will not only have to be technologically superior but also more responsive to shrinking defence budgets. Simulation systems, with new technologies to keep costs down, can strongly contribute towards meeting both types of requirements, as I will discuss later.

3. Critical Issues of Military Flight Training

The aforementioned Military Flight Mission Requirements not only demand considerable training to enable the pilot to fulfill his task, but they also call for his practising this skill under peacetime conditions.

Although flight training accidents have been accepted in the past as a price of readiness, this price appears to be rising beyond the level of public acceptance. These flight safety aspects in combination with environmental issues such as noise have strongly reduced the public and political support that the NATO Air Forces in Europe deserve. Further details are shown on the viewgraph (Figure 7).

The only way to alleviate the discrepancies between the military training requirements of combat readiness and peacetime training limitations in Europe is by making greater use of piloted simulation.

The most challenging flight training requirement is the consequence from the German restrictions on low-level flying and the request issued to its NATO allies for them to observe the same rule while flying in German airspace. Low-Level Flight Training in the simulator requires high-fidelity simulation. We will hear more about it later.

But it must also be stated that even the most sophisticated aircraft can be rendered worthless if its pilot is more or less marginally trained on ground-based simulators. Simulator time cannot compensate for a lack of real flying experience. Therefore, shifting too much flight time to simulator time could have adverse effects on the morale of air crews and their decision to remain in the services.

4. Opportunities for Flight Vehicle Development and Verification Simulation

As I said earlier, the wide variety of applications of piloted simulation includes the support of flight vehicle system development and verification as well as allows varying grades of aircrew training. Both areas will be discussed in special sessions of this symposium.

To begin with, the potential and opportunities for flight vehicle development support are shown on the viewgraph (Figure 8). Complementary simulation tools and their increasing complexity become necessary if a higher degree of confidence is required. Ground-based hardware and pilot-in-the-loop engineering simulations, when used effectively, already

allow tremendous savings to be made in development costs and time.

In-flight simulation becomes necessary as a final verification tool whenever ground simulators may provide misleading or even erroneous answers. Special lessons have been learned whenever new flight control system architectures and characteristics have been dominated by initial abruptness, excessive time delays and nonlinear effects. In such cases large amounts of control surface activity can lead to control surface rate limiting and the pilot has either been incapable of providing adequate control or he has coupled with the aircraft response. This kind of critical man-machine coupling is described as pilot-induced oscillations.

The Swedish company Saab-Scania recently used a USAF in-flight simulator because the 1989 Gripen accident was obviously related to flight control system peculiarities that they had not been able to discover in thousand of hours of ground-based simulations.

A recent first International Symposium on In-Flight Simulation hosted by DLR in Germany provided a unique expert forum for test pilots, flight test and simulation engineers from industry, governments and research organizations to discuss the importance of piloted simulation for flight vehicle system verification - using both ground-based and in-flight simulation in complementary roles [2].

The next viewgraph (Figure 9) indicates application areas for verification testing where piloted simulations have proved to be very successful.

As an example, the last item on this chart has been successfully implemented by the US Army. During the evaluation of the two industry proposals for the future Light Helicopter (LH) the assessment of the piloted simulators played a key role and was one of the most important selection criteria for the award of the full-scale development contract. The US Army has stated that it will save about one billion US Dollar by not building demonstrators [3].

The next two viewgraphs are related to the third and fourth items on this chart, concerning the upgrading of certification standards which are not readily applicable to modern technology subsystems such as fiber-optical flight control systems.

In the rare in-flight photo (Figure 10) the fixed-wing and rotary-wing in-flight simulators VFW614 ATTAS and BO105 ATTHeS of the German Aerospace Research Establishment DLR are shown. Both flight vehicles are involved in various national and international research programmes.

The full-authority fly-by-wire flight control system and its actuators for ATTAS were designed in the early 1980's whereas the yaw-control channel of the helicopter simulator ATTHeS is a fly-by-light system of the late 1980's.

As you can see on the close-up view (Figure 11) the quantum jump in actuator technology from ATTAS to ATTHeS is obvious. The ATTAS actuators still need separate large size electronic control units for redundancy management whereas the ATTHeS electro-optical control unit is fully integrated within the tail-rotor actuator system.

In order to get such smart actuator technologies for flight critical systems certified in a reasonable time frame an early dialogue between the system designers, integrators and acceptance authorities is highly beneficial. Again, ground-based and, ultimately, airborne piloted simulation will be the decisive tools for providing evaluation data and criteria.

5. Opportunities for Aircrew Training Simulation

The drive to reduce training costs requires the increased use of all kinds of simulators from the so-called Electronic Classroom, representing computer-based ground training systems, up to Embedded Training which provides in-flight full mission training on complex air weapon systems under real environmental and threat conditions.

The application spectrum of Aircrew Training Simulation is shown on the viewgraph (Figure 12). For many years emphasis was placed on the enhanced realism of full-capability training simulators. Increasing computer efficiency nowadays permit a greater degree of confidence and realism due to higher fidelity in motion and outside scenery generated by visual systems. As a result, advanced-capability simulators required for Full-Mission Rehearsal Training are becoming more complex and costly.

On the other hand, simulator companies have recently entered the market with new families of reconfigurable simulation systems using reprogrammable and portable software, offering new prospects of lowering overall costs. The fastest growth in use will be with the low-end simulators for part-task or basic flight training.

Nevertheless, while simulator time for primary training will not substitute actual flight time, it will enhance it and make it more efficient.

An excerpt from the wide range of simulator applications for aircrew qualification and training is shown on the following viewgraph (Figure 13). The main simulator training objectives are related to the familiarization of the pilots with flight vehicle system operations, flight characteristics and emergency procedures. Increased emphasis will be placed on crew co-ordination and mission management. Enhanced automation and advanced avionic technologies are creating a need for better understanding and training in crew awareness of how to interact with the aircraft.

The most challenging simulator training requirements are coming from low-level flight missions such as Terrain-Following High-Speed Flights or helicopter Nap-of-the-Earth flights. Due to the strong political issues associated with low-level high-speed flight training in Europe to which I drew attention back in

my introductory remarks, it seems to be justified to spend another five minutes on this subject.

Since the German restrictions of low-level flight training have been imposed, not only the German Air Force, but also several NATO air forces have been looking increasingly at the degree to which simulators could replace or at least reduce the amount of low-level flying exercises.

From the general requirements and problem areas shown on the viewgraph (Figure 14) it can be concluded that new frontiers have to be approached in order to achieve pilot acceptance for ground-based low-level high-speed training simulation.

Low-level flight consists of a mass of highly detailed visual cues being continuously up-dated in the pilots brain. Scene details are used to obtain height and speed cues. Peripheral vision provides spatial and additional speed cues. In the terrain-following flight mode and due to low-level turbulence the pilot is also subject to dynamic variations of vertical accelerations which lead to specific motion cueing via his vestibular system.

Both impressions, that is visual and motion cueing, must be accurately reproduced in a ground-based Low-Level Training Simulator. A lack of time correlation or disparity between visual and motion cues - such as visual scene delay - can cause simulator-induced sickness. The tendency for simulator-induced sickness seems to be strongest for the more experienced pilot who may have more expectancy patterns stored in his brain.

Another fundamental issue for low-level training simulation is related to variations in human information-absorption and decision-making during "synthetic" flight conditions in comparison to the real world. Also, it is probably not sufficient to produce a similar performance in the simulator as in flight. It is also necessary that the pilot adopts the same control strategy.

In order to gather information about how much progress must be made before visual systems and motion system enhancements approach the simulator fidelity needed to replicate low-level flying the German Government has initiated the development of a testbed for a future ground-based Tornado low-level training simulator. The project is being conducted by CAE Electronics GmbH and the Tornado Test Simulator arrangement can be seen on this viewgraph (Figure 15).

By utilizing the CAE-Link Fibre Optic Helmet Mounted Display for each crew member to display high-dynamic and resolution visual scenes it is hoped to bring new dimensions to visual realism [4]. Furthermore, as the visual system and the crew are positioned on the same six-axis motion platform it seems to be easier to harmonize the vestibular and visual sensations of motion with a lower probability of simulator induced motion sickness.

If the customer evaluation proves to be successful, there are plans to upgrade the in-service simulators of the German Air Force and Navy.

Let me finally give you some generic thoughts about future training systems which have to meet certain performance criteria in order to allow

- training for complex air warfare,
- preparation of aircrews for "red flag" type exercises, and
- optimization of mission parameter sets.

These performance criteria are shown on the viewgraph (Figure 16). They give an indication of technical problem areas, where detailed research is required. The aim of this research is to improve the realism of present training systems in some fundamental areas such as

- realistic scenarios to be composed from standardized data bases,
- "artificial intelligent" targets with inherent maneuver logics, and
- networking of operational training simulators in order to increase the number of players taking part in an exercise.

Here in Europe we intend to conduct this research as part of the "EUCLID" research programme.

The potential of airborne simulation of combat mission segments requires (Figure 17)

- a relevant scenario with simulated electronic warefare components to be generated and displayed,
- air targets as well as ground targets on-board and their tactical behaviour displayed to the aircrew,
- situation oriented avionics/sensors to be managed and, if available, integrated, if not, to be simulated,
- the firing logic of friendly and enemy weapon launch solutions to be simulated and displayed, and
- the offensive and defensive maneuver and attack profiles to be calculated on-board and displayed in a format so that the aircrew can interpret the steering commands and maintain situational awareness.

Technical requirements include

- computer hard-/software to generate the environment and
- display technology to interface the aircrew with the in-flight simulation system.

Problem areas are mainly associated with the

- availability of flight cleared hard-/software.

6. Conclusions and Recommendations

Ladies and gentlemen,

I would like to conclude by challanging you all the AGARD and expert community. I ask you to discuss the four questions shown on the viewgraph (Figure

18) concerning not only simulator capabilities and human limitations but also aspects of affordability:

- What are the minimum equipment requirements for development simulation and training simulation?
- Can simulator fidelity be improved by introducing new cost-effective enabling technologies?
- Are there technical or training options available to increase pilot acceptance for low-level high-speed flight simulation?
- What actions should be taken to enhance standardization and implementation of full mission simulation facilities for common and complementary use within the NATO forces?

With my final viewgraph (Figure 19) I would like to compliment AGARD and its Flight Mechanics Panel and to thank it for all the efforts it has made in the field of Flight Simulation in order to

- provide a cost-effective forum for scientific/technical information exchange,
- advise NATO governments on required research and development,
- stimulate co-operative and cost-effective multinational research and development ventures and, finally,
- accumulate multidisciplinary simulation expertise in its various Technical Panels.

It is appropriate to cite the Honorable Robert C. Seamans, formerly Secretary of the United States Air Force, M.I.T. Professor and Dean of Aero- and Astronautics, and US National Delegate to AGARD (1966 - 1969), who forty years ago exactly had this to say about development simulation [5]: *"It is highly desirable to check the flight result against simulator results so that valuable flight time is not wasted".*

Thank you for your kind attention and I wish you every success for your symposium.

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Discussion of the Wright Brothers Lecture of W.Bolley: Aerodynamic Stability and Automatic Control
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8. Figures

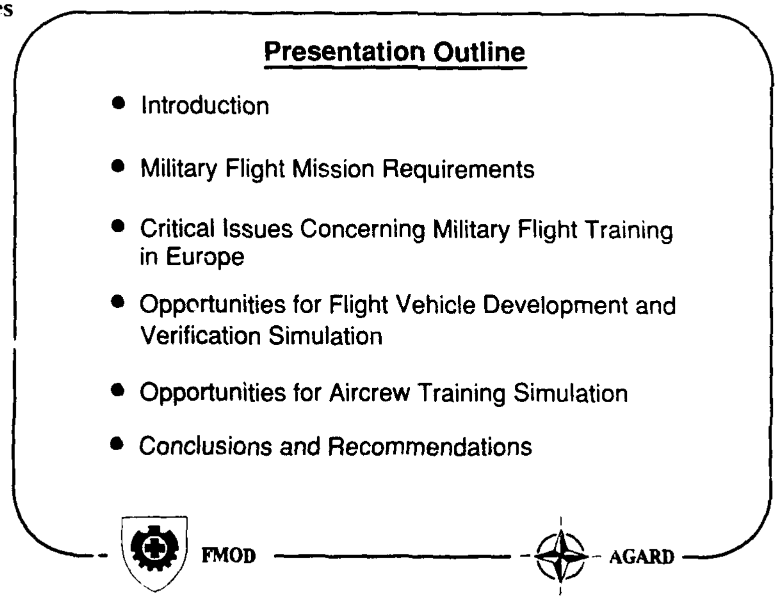
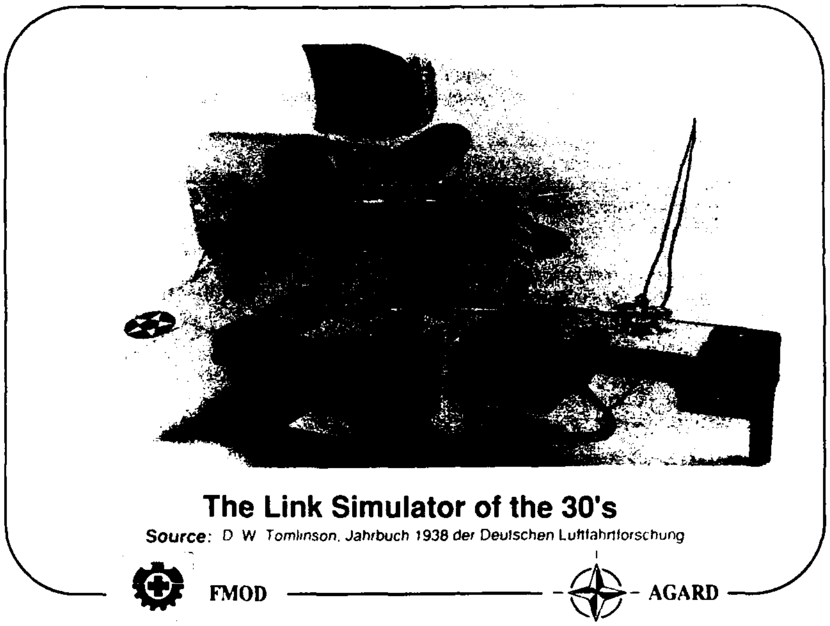


Figure 1



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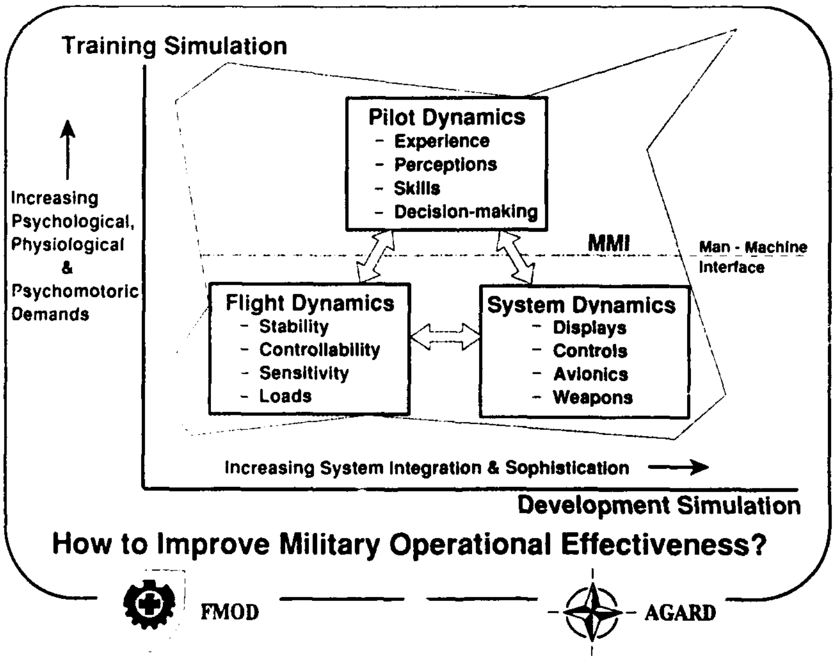

Figure 3

Piloted Simulation - The Role of AGARD (Part 1)

Road Map of Flight Mechanics Panel (FMP) Activities:

- Some 30 Documents (1956 - 1991)
- Highlights:

Symposia:
- ○ Piloted Aircraft Environment Simulation (1978)
- ○ Flight Simulation (1985)
- ○ Piloted Simulation Effectiveness (1991)

Working Groups:
- ○ Fidelity of Simulation for Pilot Training (FMP/AMP WG 10, 1980)
- ○ Characteristics of Flight Simulator Visual Systems (FMP WG 10, 1981)
- ○ Validation of Simulation Systems (FMP WG 16, 1992)
- ○ Piloted Simulation in Low Altitude High Speed Mission Rehearsal (FMP WG 20, 1993)

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Figure 4

Piloted Simulation - The Role of AGARD (Part 2)

Complementary Contributions from other Panels:

- AMP AGARDograph: The Use of Simulators for Training In - Flight and Emergency Procedures (1980)
- AMP Symposium: Motion Cues in Flight Simulation and Simulator Sickness (1987)
- GCP Symposium: Computer Aided Design and Simulation (1990)
- AASC Workshop: Low Level Flight Training (1989)
- AASC Study No. 34: Reduction of the Environmental Impact of Operational Flying Training (1992 / 1993)

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Figure 5

Military Flight Mission Requirements

- **Air Force**
  - Interdiction
  - Counter Air
  - Reconnaissance
  - Air Lift
- **Navy**
  - Anti Submarine Warfare
  - Search and Rescue (SAR)
  - Combat Rescue
  - Over the Horizon Targeting
- **Army**
  - Anti Armor
  - Escort
  - Transport
  - Fixed Target Indication (FTI)
  - Moving Target Indication (MTI)

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Figure 6

Critical Issues Concerning Military Flight Training in Europe

- **Flight Restrictions** due to
  - Limited Combat Training Ranges
  - Dense Air Traffic
  - Flight Safety Aspects (Air Crashes)
- **Flying Hour Reductions** due to
  - Declining Budgets
  - Rising Costs of Flight Operations)
- **German Restrictions on Low Level Flying** due to
  - Greater Environmental Awareness (Noise Annoyance)
  - Increasing Public Reluctance and Opposition
- **Adverse Effects on Aircrew Morale ?**

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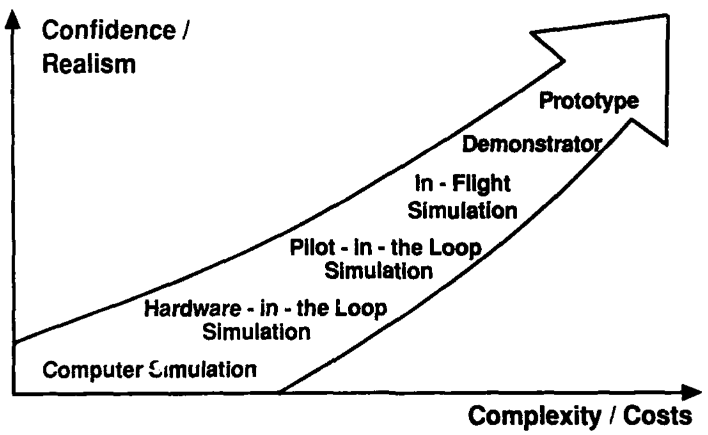
Figure 7



Flight Vehicle Development Simulation

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Figure 8

Use of Piloted Simulation in Verification Testing

- Definition of Handling - Qualities Requirements
- Flight Control and Subsystem Assessment Modification and Up - Grading
- Flight Vehicle Subsystem Acceptance Testing and Certification
- Development of Certification Standards
- Validation of Design and System Capabilities for Contractor Selection

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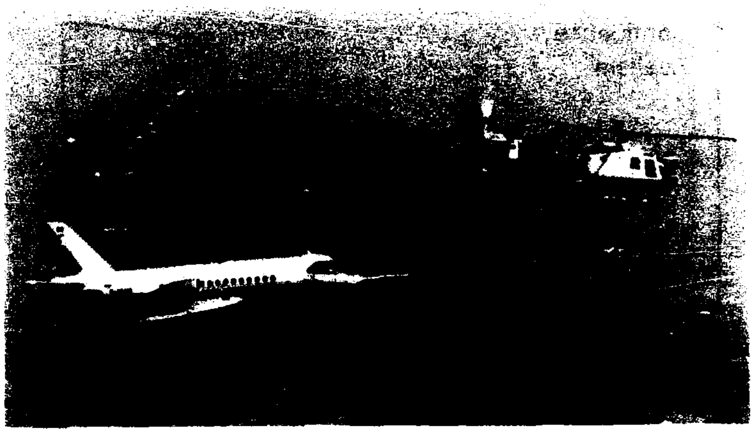
Figure 9



DLR In - Flight Simulators VFW 614 ATTAS and BO 105 ATTHeS

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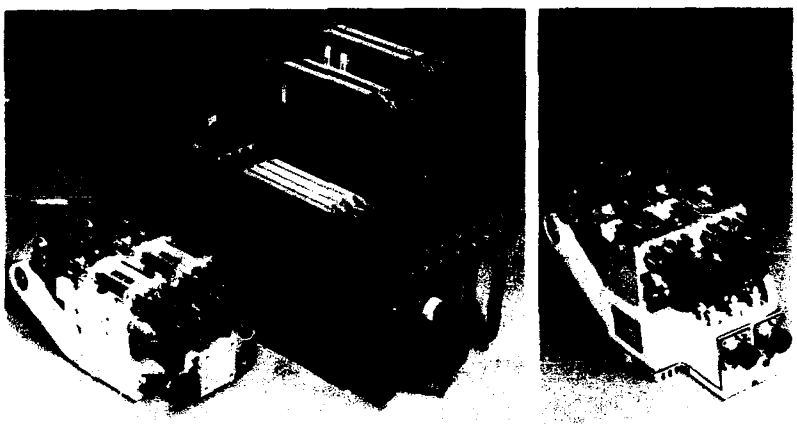
Figure 10



Advances in Digital - Electrohydraulic Actuator Systems for In - Flight Simulators

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Figure 11

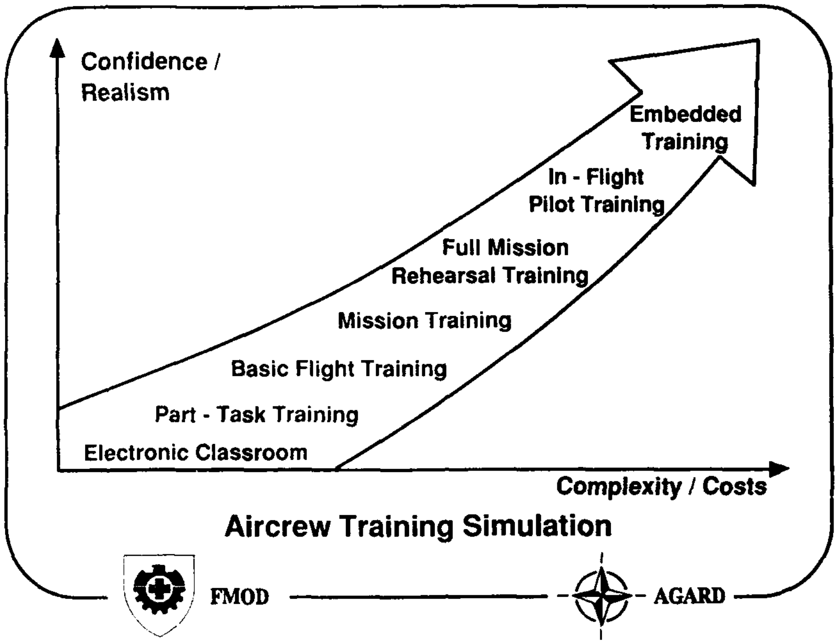

Figure 12

Use of Piloted Simulation for Qualification and Training

- Cockpit Procedure & Proficiency Training
- Emergency Procedure Training
- Crew Coordination & Mission Management Training
- Type & Weapons Training

- Familiarization with New Technologies (Automation)

- Low Level Flight & Mission Rehearsal Training

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Figure 13

Terrain Following Training Simulation

General Requirements

- Accurate Modelling of A/C and Environmental Dynamics
- Effective Visual Description of Outside World
  - Large Field of View (FOV)
  - High Resolution Computer Generated Imagery (CGI)
- Realistic Motion Environment
  - High Fidelity Motion

Problem Areas

- Simulator Induced Sickness (SIS)
- Neural Mismatch (e.g. Neural Storage of Experience)
- Biodynamic Interferences (e.g. Pilot - Induced Oscillations)
- Variability of Information and Control Strategies

FMOD — AGARD

Figure 14

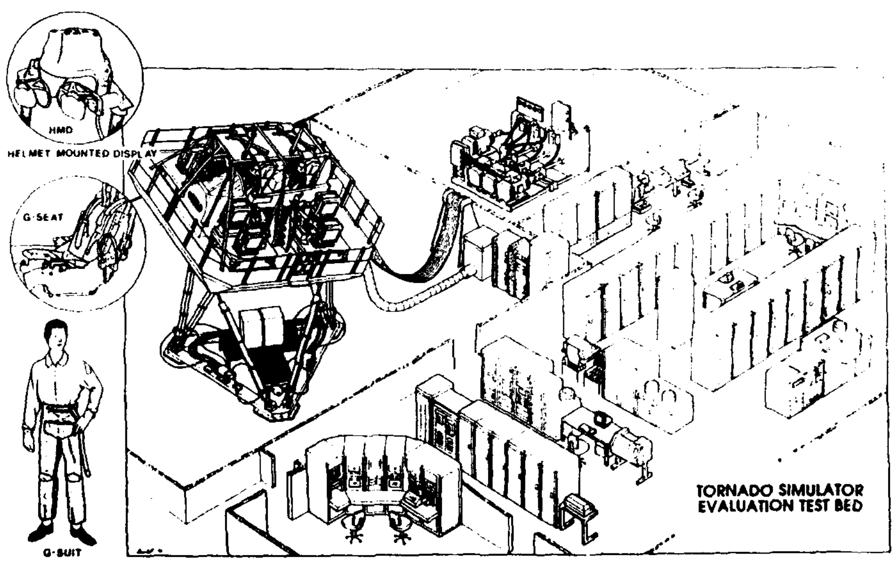

Figure 15

Simulation of Complex Air Warfare

Performance Criteria and Technical Needs of a system for complex air warfare training

- Realistic
  - scenarios
  - environment
  - cockpits
- Fidelity of simulation
- Representative number of players
- Validation, briefing, debriefing
- Optimum mission

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Figure 16

Airborne Simulation of Combat Missions

On - board simulation of relevant mission segments by generating and displaying

- Scenario / electronic warface elements
- Opponents / targets (airborne and ground targets)
- Situation oriented avionics / sensor management
- Enemy and friendly weapon capabilities (firing logic)
- Offensive / defensive maneuver / attack profiles

Technical Requirements

- Computer hard - / software to generate the environment
- Display technology (head - down, head - up, helmet mounted) to interface the aircrew with the airborne simulation system

FMOD — AGARD

Figure 17

Recommendations

Challenges to the AGARD and Expert Community here today concerning Aspects of Affordability:

- What are the **Minimum Equipment Requirements** for
  - Development and Verification Simulation
  - Pilot Training Simulation
  - Complex Air Warfare Simulation?
- Where are **Cost - Effective Enabling Technologies** to Improve Simulation Fidelity ?
- What Action must be taken to **Increase Pilot Acceptance** of Training Simulation ?
- What **Means of Simulation Facility Concentration and Standardization** may improve NATO Military Operational Effectiveness ?

FMOD — AGARD

Figure 18

Conclusions

- AGARD plays an **Indispensable Role** in the Development of Piloted Simulation
- AGARD provides a **Cost - Effective Technical Forum** for the NATO Piloted Simulation Community
- AGARD should continue to **Accumulate Multidisciplinary Simulation Expertise** in its various Technical Panels

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Figure 19

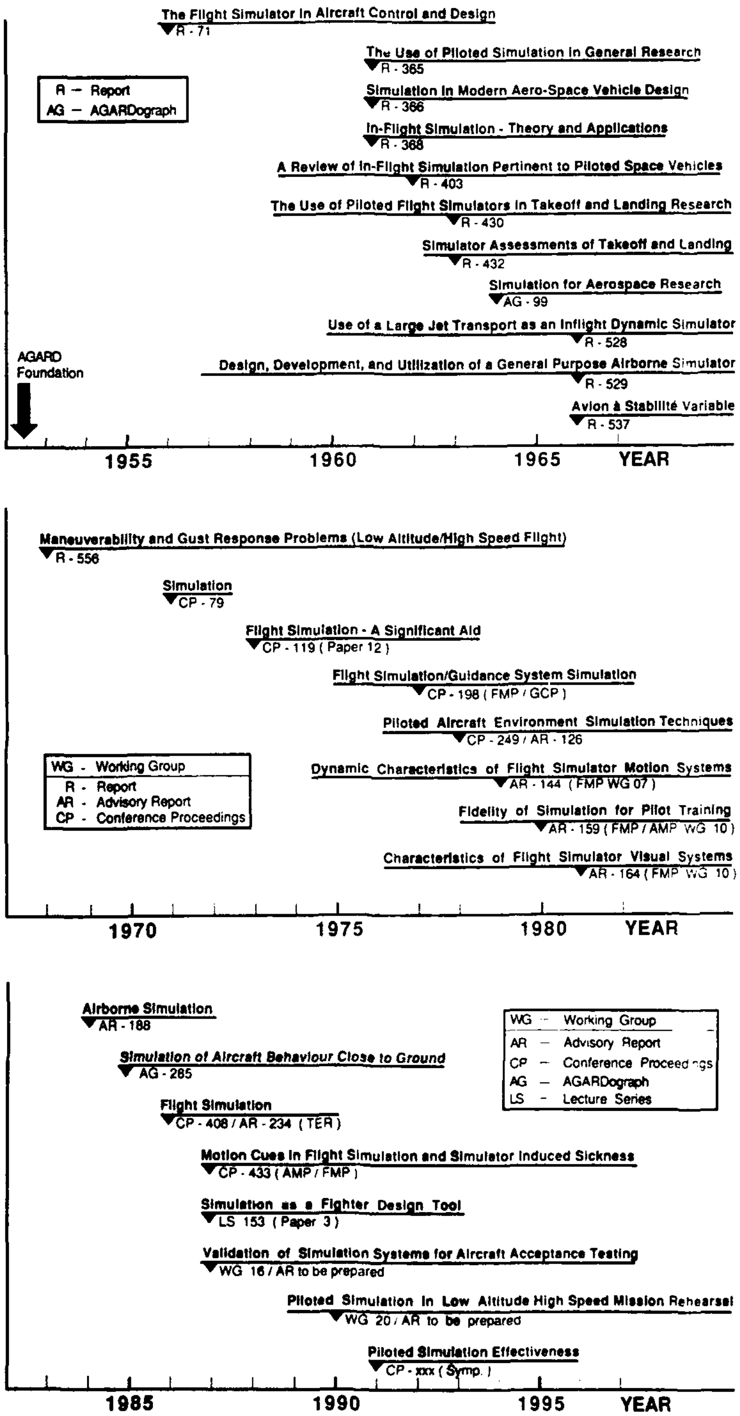

Table 1: AGARD Flight Mechanics Panel: Activities in Piloted Simulation

Piloted Simulation Effectiveness
Development Applications and Limitations

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Many years ago President John F Kennedy hosted a dinner for a gathering of scientists at the White House - a gathering that may have represented intelligence and achievement on the same level as today's gathering here. His words on that occasion were "This may represent the greatest concentration of brainpower here since Thomas Jefferson dining alone." I recently had the opportunity to tour Jefferson's home, Montecello, with a Jeffersonian expert, Billy Wayson. During the course of my tour, I became more aware of Jefferson, the scientist. He was, appropriate to this gathering, a great internationalist. He assimilated the culture, technology and systems of Europe and attempted to transplant them to North America. He was a tinkerer and an experimenter. Like many of us, he experimented on the system level and collected vast amounts of data. He certainly faced a problem we face today - the difficulty of finding meaning in all the data he collected. For all his brilliance, he died a pauper. He was unable to conduct experiments except on a full scale - a scale so vast that his experiments consumed his resources.

We have a problem similar to Jefferson's today. Development of complex military systems is difficult. Some problems could be solved if we had a full scale, fully instrumented war to provide data. But deriving data from even the short, idiosyncratic war in the Middle East this year was a problem. Even if the data are available, turning data into useful information remains a problem. Simulation today provides us with the best possible means of understanding masses of data and designing for the wartime environment. Simulation also provides a means to make sense of the vast amounts of technical data we are able to generate.

Simulation plays another role today, as an aid to strategic planning. With numerous technologies competing for the investment dollar, simulation provides us with a means to understand the impact of technologies not yet developed. Once that strategic investment decision is made, simulation often becomes part of the development process.

Systems today often begin with rapid prototyping. In rapid prototyping the operation of a system may be functionally modeled without coming to grips with how the system will be designed or what the components will be. Rapid prototyping allows the characteristics of a complex system to be understood before it is designed and built. Even if we choose to omit the rapid prototyping step, modern systems are often too complex and expensive to develop without running a model of the full-up system before the system is built. That model often starts as a software emulation of the full up system. Then, as individual hardware and software modules are completed, they can be substituted for their software emulation modules.

The simulation approach may be essential to development of modern systems but that is not the key issue of this conference. That key issue is manned simulation. The most complex mechanism that must be integrated into today's systems is the man. His input/output connection is undefined, his gain constantly changes, no two modules are alike and accurate transfer functions have yet to be written. Sometimes he has a good night and the following day is less good. Sometimes personal considerations overwhelm normal operating characteristics. Nonetheless, man is the most adaptive, fastest learning and best logical system yet invented and it is worth our effort as designers and engineers to tap into that powerful computer that is the human brain.

Some of you may have read the recent novel "Day of the Cheetah." In that novel, the pilot's reasoning and computing capacity was integrated with that of the airplane through a complex and demanding direct connection to the brain. In real life today we work through more conventional input/output devices to include the pilot and his reasoning power as part of the system. We need a means of measuring the demands put on the pilot's input/output ports - visual, audible and kinesthetic - and we must be able to assess whether the task the pilot is assigned can be done in the highly demanding environment of the cockpit. Simulation is the key to bringing the man - a real man - to the development process.

The remainder of my presentation will be a survey of some simulation systems used in the United States with full recognition that similar and in many cases superior systems are in use elsewhere. Simulators take on various aspects, depending on the task at hand. I will look at various mechanizations of simulation and attempt to relate them to the nature of desired outcomes. Finally, the question "Why simulate?" must be addressed.

In preparing for this presentation, I paid special attention to simulators operated by the US government - the military services and NASA. I did not spend much time at contractor facilities although those facilities provide some of the US's most capable simulation. For the most part, those facilities are similar to the government facilities I will discuss.

Fitting the simulator to the task is key to getting meaningful results. The range of simulators available goes from the highly capable, ubiquitous large dome with full projection capability to what I call the "folding chair simulator" - a display monitor, a joystick and the appropriate computing hardware and software. At Wright Laboratory we use a "folding chair" simulator for rapid prototyping pilot display formats. These displays can be mechanized in hours and can be designed to move and change as they might in flight. This rapid screening allows a large number of concepts to be tested in minimum time.

A simple simulation at NASA Dryden was used to explore control of aircraft with flight controls largely disabled. This simulation showed it is possible to control and possibly land an airplane like a Boeing 707 or a McDonnell-Douglas F-15 using power changes alone. Much more complex simulation may take place before this capability is next heard from but interesting possibilities have been raised. The concept showed promise and today our laboratory is engaged in a joint research project with Dryden to further explore the idea. The key was the ability to easily and quickly develop a simulation to explore the concept without a large commitment of resources.

One issue that often is raised when simulation is being considered is the necessity for motion. Today's dome simulators so completely stimulate human visual sensors that the absence of motion often goes unnoticed. Nonetheless, we at Wright Laboratory maintain both a domed and a motion based simulator for specific purposes. We feel the motion based simulator is better for many pilot-in-the-loop flying qualities tasks while the domed simulator is better for complex systems operation and battle management tasks. Perhaps the extensive use of fixed base, domed simulators today reflects a concentration on systems integration and battle management as a force multiplier.

I have had recent experiences that gave me a first hand opportunity to assess the issue of motion. At NASA Ames, I had the opportunity to fly their VMS - a large range of motion simulator especially designed for Vertical and Short Takeoff and Landing flying qualities. As luck would have it, the simulation underway was of a Harrier. It had been eight years since my proficiency in the Harrier had lapsed but upon entering the simulator - with motion turned off - I found that it was still possible for me to control the machine. I found myself able to perform all the basic takeoff and landing maneuvers but, as might be expected, with nowhere near the smoothness of control I like to remember myself as showing during my flight testing days. Then, after about ten minutes, the simulator operator asked if I was ready for motion. I consented and it seemed to me as if a very powerful and effective set of stability augmenters had been engaged. The airplane immediately stabilized and flew like I seemed to remember - or at least like I wanted to remember myself flying. The addition of motion cues provided me, as the pilot in the loop part of a system, with an additional channel of feedback that substantially improved system qualities.

The second experience at Ames that particularly impressed me was flying the Crew Station Research and Development Facility. That system is used to address both flying quality issues and systems integration and battle management issues - primarily for helicopters. The unique aspect of the Crew Station Research and Development Facility is that it does not use an externally projected image. The system is, by today's popular nomenclature, a virtual reality system. The pilot wears a helmet that projects separate computer generated images, via laser light valves, into each eye. When the pilot turns his head, the generated image changes to follow his head motion. The system was mechanized as a helicopter with a single four-axis controller replacing the cyclic and collective controls. An additional friendly helicopter was mechanized and the terrain included a small European village. As I maneuvered around the terrain, I quickly noticed an overwhelming sensation of motion. I could distinctly feel forces applied to my body. I had not noticed any provisions for motion as I got into the seat nor had my briefer mentioned motion. I determined I would figure out for myself whether I was moving. By twisting my head, I was able to adjust my field of view until I could see around the projected image. In the background I was able to see some mechanical components of the system and they were definitely not moving. The forces I felt must have been generated as I braced myself against anticipated accelerations. To finish the story, I established beyond a doubt the compelling nature of the visual display when I executed some high rate maneuvers and immediately experienced motion sickness.

Does this prove motion is not necessary? Not at all. In fact, motion sickness is well known to be caused by a disparity between senses. My eyes saw motion that my body did not feel. However, it is curious to me that similar experiences in fixed base domed simulators have not resulted in the same sensations or the same nausea.

Finally I want to mention a recent opportunity to fly a simulation of the HL-20 at NASA Langley. The HL-20 is a "space taxi" concept that might be used to ferry people to and from a space station. After a year of development, the system concept had been considerably refined as a result of simulation, including some substantial changes to the design of the vehicle. The simulation addresses the full range of aerodynamic and flying qualities issues and is well on the way to providing a means to train test pilots. My own learning curve was very rapid, progressing in three tries from a barely safe standard approach to a smooth touchdown from an approach started with low air speed and low on glide path. The touchdown motion was especially convincing, providing instant feedback on rate of descent that was much more immediate and meaningful than the digital readout in the cockpit.

When we speak of motion based simulators, we are usually talking about simulators with a limited range of motion. The intent is not to duplicate accelerations the pilot feels but simply to provide some cues that allow the pilot to use more of his senses and more accurately duplicate the sensations of the airplane. Sometimes it may be desirable to provide a nearly exact duplication of accelerations along with a high fidelity visual environment. The choice for this situation is

the in-flight simulator. We at Wright Laboratory take pride in our pioneering of inflight simulation as a tool to develop flying qualities criteria as well as to simulate specific airplanes and their control systems. Our current in-flight simulation stable of airplanes includes the oldest airplane in the US Air Force, the NT-33. Our other in-flight simulator is based on a twin turboprop transport. Like ground based simulators, these airplanes have limitations and must be used intelligently. In an attempt to increase our capability to simulate today's high performance systems, we are replacing the NT-33 with a new in-flight simulator based on the F-16. The VISTA will have a substantially increased simulation flight envelope. First flight of VISTA is scheduled for next month.

To no one's surprise, the cost of conducting a simulation rises as the fidelity of simulation rises. Simulation represents a substantial cost in development of current airplanes but many of us associated with the development process believe strongly that simulation provides good value. Some of us would maintain that simulation is frequently underutilized. Certainly systems have been developed with problems that needed expensive correction late in development - problems that could have been found and corrected using simulation. With that thought in mind, I'd like to spend a few moments considering the issues that simulation is used to address.

We've already spoken of simulation as a strategic planning tool. Simulation can help us identify high payoff technologies for further investment. One example of this is the extensive research that has been done in simulation of agile aircraft. One interesting aspect of this simulator research is that at least one early simulation of enhanced agility was inadvertent. NASA Langley had one of the first dual dome simulators in the US and was using it for air-to-air evaluations. The simulation they were running was the F-14 against the MiG-21. Since the F-14 was a more recent aircraft with a concentration on air-to-air agility, researchers expected it to win most engagements. That turned out not to be the case. The MiG was winning almost all the engagements. This was a matter of serious concern for the folks running the simulation. In fact, there was initially some concern that sensitive issues were involved. Engineers quickly rechecked the simulation data base. It turned out that the aerodynamic data of the MiG-21 was not well known and had been estimated. The non-linear portion of the flight regimes had been projected as linear. That MiG had derivatives that stayed linear even when stall thresholds were exceeded. NASA aerodynamicists quickly understood that linear derivatives at high angles of attack might be of value. Further simulations have verified the expected payoff of flying at conditions outside what we consider the normal flight envelope. Those potential payoffs were projected as powerful enough that today we are testing the X-31, an airplane designed to have control power through a very large flight regime.

As I surveyed various users of simulation in the development process, I found a recurring theme. Simulation is an excellent medium for communication between the test pilot and the engineer. A lack of communication between these communities has been implicated in many problems, ranging from poor specifications that wasted time and money to poor execution resulting in loss of aircraft. Flight test organizations are particularly fond of using simulation to plan, practice and anticipate technical issues in flight test. Both NASA Dryden and the Air Force Flight Test Center at Edwards Air Force Base make extensive use of simulation. The X-29 simulator at Dryden was involved in clearing the X-29 to 66 degrees angle of attack. The Short Takeoff and Landing F-15 was similarly cleared by the Air Force Flight Test Center through its flight test sequence. The simulator served as the library of analytical and wind tunnel results, modified to reflect flight test results to date. The simulator was used to practice missions, to develop procedures, to check the consequences of errors in projected data, to train test pilots and test engineers and to provide a way of quickly generating expected results for comparison to flight.

During these two flight test programs, I was able to get a management level assessment of progress by flying the flight test simulators myself. By discussing my observations with pilots and engineers, I could understand areas of uncertainty and controversy and, if necessary, I could preview the likely results of any management guidance I might plan to give. I was able to do all these things quickly, efficiently and with minimum chance of misunderstanding because of the ability to communicate using simulation. In these cases, simulation became a powerful tool for management oversight.

I'll close with a quick review of the benefits of simulation. Simulation allows us to make strategic investment decisions - to answer the question "What if I had a system that would...?" Next, simulation can be used in rapid prototyping; "If I had such a system, this is now it might function." Simulation often provides the first system mechanization by laying out and connecting the functional modules. Step by step, those software modules can be replaced by hardware as the system takes shape. Man can be designed into the system through use of simulation, checking at each stage in the design process to make sure man is being integrated into the system properly. During system test and development, simulation provides a means of comparing forecast and actual data, of augmenting communications between pilot and engineer and of documenting final results. Simulation is there before the program starts and continues to exist as the program comes to maturity. During the next few days we will have the opportunity to consider several applications of simulation. Keep in mind, as you consider each one, where that simulation fits in the continuum I have described, what the prior step in simulation may have been and what the next step is likely to be.

As a final note I would like to acknowledge superb cooperation from NASA centers at Ames, Langley and Dryden and from the Air Force Flight Test Center. These organizations provide constant cooperation and support for all of Wright Laboratory's initiatives and went out of their way to be helpful to me.

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UTILITY OF GROUND SIMULATION IN FLIGHT CONTROL PROBLEM IDENTIFICATION, SOLUTION DEVELOPMENT AND VERIFICATION

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SUMMARY

The Air Force Flight Test Center (AFFTC) Flying Qualities Simulator is consistently used prior to and in conjunction with flight test to identify aircraft flight control problems and also to develop, test, and validate solutions to these problems. The subject of this paper is an example of how ground simulation was vital in developing an effective software modification to eliminate a potentially dangerous aircraft flight control anomaly. Through simulation, an in–flight uncommanded pitch oscillation incident was investigated and the source of the problem was identified. A potential solution was tested and validated by utilizing the simulator prior to flight test.

Additional benefits were gained due to simulation studies. The project pilots were able to practice test maneuvers and emergency procedures essential to the flight test program. The preliminary work accomplished by ground simulation correctly predicted the effectiveness of the software modification and ensured the success of an efficient and valid flight test program.

LIST OF ABBREVIATIONS

AFFTC	Air Force Flight Test Center
TAC	Tactical Air Command
DFLCS	Digital Flight Control System
MSL	Mean Sea Level
KCAS	Knots Calibrated Air Speed
TEMS	Test and Evaluation Mission Simulator
HUD	Head–Up Display
DBU	Digital Backup
CR	Cruise Configuration
PA	Power Approach Configuration
USAF	United States Air Force

INTRODUCTION

A Tactical Air Command (TAC) fighter aircraft equipped with a Digital Flight Control System (DFLCS) encountered a sustained uncommanded pitch oscillation while performing air combat maneuvers. The pilot, mistaking the unexpected motion as a possible pilot induced oscillation, immediately released the control stick to take himself out of the loop. However, the pitch oscillation continued for 20 seconds before damping out. Variation in peak load factor during the oscillation was approximately 2 to 3 g's with a maximum change of 6.5 g. The frequency of the oscillation was 1 cycle per second and occurred at 12,000 feet MSL and 330 KCAS (Figure #1). The pilot terminated the mission and no further pitch oscillation incidences were reported during the remainder of the flight. Once on the ground the aircraft was thoroughly inspected for any anomalies, but none were found.

PROBLEM IDENTIFICATION

Both the AFFTC and the aircraft manufacturer conducted investigations of this flight control phenomena. Although a time history of this event was retrieved from the aircraft seat data recorder, this particular model of fighter aircraft did not record any control stick inputs. Thus, the only record of what aircraft motions excited the oscillatory mode was provided by the pilot's report and the recorded aircraft angles, rates, and control surface deflections. The pilot was uncertain of the control inputs that were executed due to the fact that he was concentrating on the target aircraft. However, the pilot did state that he did not transition through the jet wake of the other aircraft. Because no anomalies were found upon inspecting the aircraft, it was believed that the problem was a unique flight control anomaly. Investigating this phenomena by means of flight test was ruled out due to the enormous expense of a trial–by–error flight test program combined with the obvious safety risk involved if the oscillation was successfully reproduced. Therefore, ground simulation was selected as the best method for this investigation.

The simulator that was used for this investigation was the AFFTC Test and Evaluation Mission Simulator (TEMS), which is a 6 degree–of–freedom, real time, fixed base, engineering simulator. The TEMS visual system is an IVEX–2000 and has a head–up display (HUD) overlay. The same flight conditions, aircraft configuration, gross

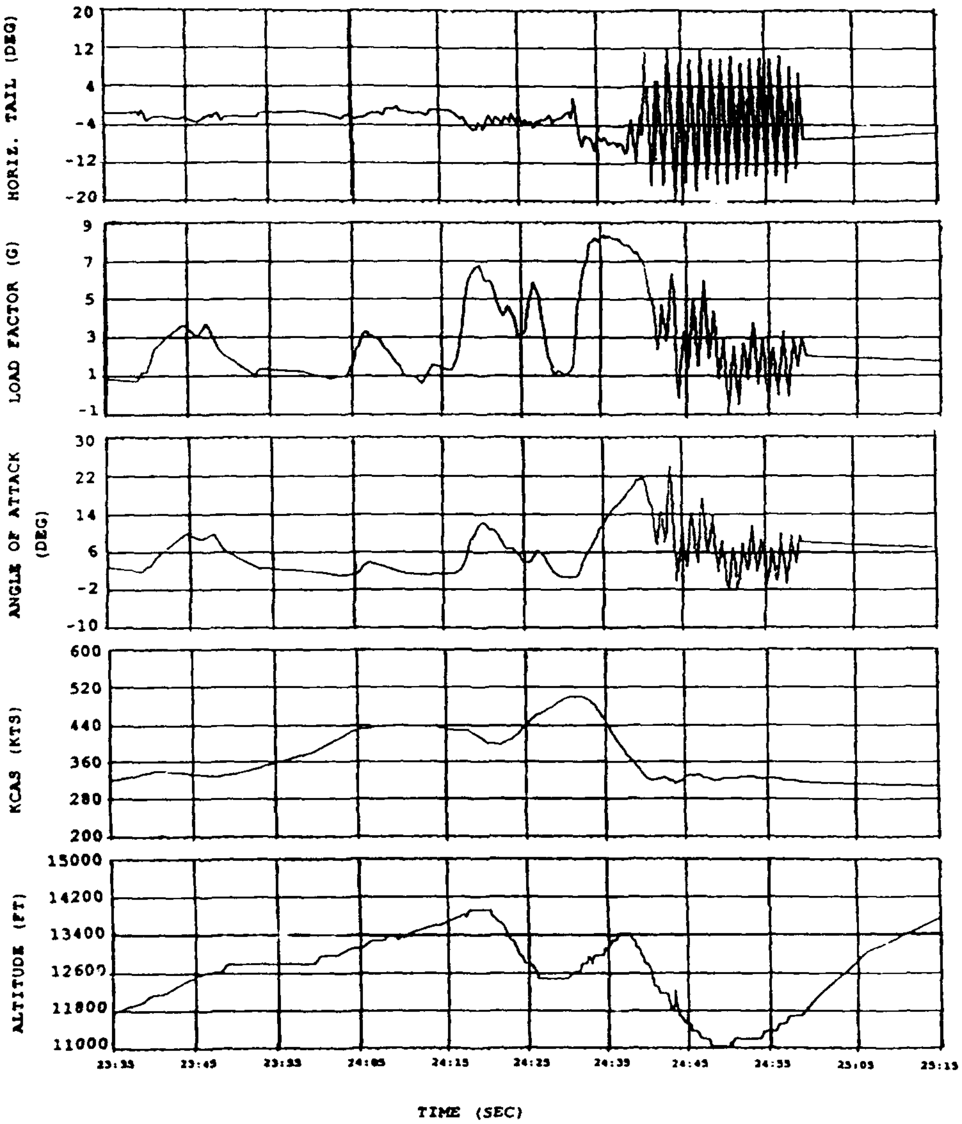

FIGURE #1: UNCOMMANDED PITCH OSCILLATION

weight, center of gravity, and moments of inertia of the subject aircraft were used to ensure validity of the simulated test. However, difficulty in reproducing the oscillation was encountered due to the lack of control stick input data. Through analysis of the aircraft recorded time history, it was determined that the horizontal tails were rate limited during the oscillation. Rate limiting is caused by large control inputs that command a control surface to react at a faster rate than the servo actuator can physically achieve. Thus, to increase the chance of reproducing the correct maneuver, the simulator flight control model was altered to cause rate limiting of the horizontal tails. By increasing the software rate limits to a rate faster than the horizontal tails could react, a phase lag was induced in the pitch axis of the flight control system and a sustained pitch oscillation was achieved.

While this approach was unconventional in method, it allowed the test team to investigate the oscillation in question, and to also determine the best control stick inputs required to produce the oscillation. Once the test team was satisfied that the control stick inputs had been optimized, the software rate limits were returned to the correct values. With minimal practice, sustained pitch oscillations were consistently obtained with the original software rate limits.

Rigorous testing followed this initial breakthrough to determine if any alternative control stick inputs or flight conditions would produce a similar oscillation. It was discovered that the severity of the oscillation was directly proportional to dynamic pressure. These simulator–produced results were then compared to the actual incident and it was determined that the two were the same. The AFFTC results were further substantiated by the aircraft manufacturer's flying qualities simulator.

Two types of maneuvers were developed to excite a sustained pitch oscillation: Cross Control Stick Reversals; and Rolling Pitch Reversals. Cross Control Stick Reversals consisted of a series of full command pitch, with roll, control inputs reversed at a rate of 1 cycle per second. Rolling Pitch Reversals were initiated with an elevated–g descending turn. When the specified load factor was reached, the pilot rolled the aircraft to wings level and executed a series of pitch control inputs at a rate of 1 cycle per second.

SOLUTION DEVELOPMENT AND VALIDATION

The process used to solve this flight control problem involved utilizing both simulation and flight test to develop, test, and validate a flight control software modification (Figure #2). Ground simulation was used to develop and optimize the control law modification. Next, the modification was extensively tested to validate that the fix was effective throughout the entire flight envelope. Additionally, flight test preparation was accomplished through simulation by developing a test plan and emergency procedures. Project pilots also took advantage of the simulator to practice these new test maneuvers and emergency procedures. Flight test was completed next and substantiated the simulation results. These results from flight test were then compared with the simulation results and analyzed to complete the process. The following sections describe in detail this process from software development to test program conclusions.

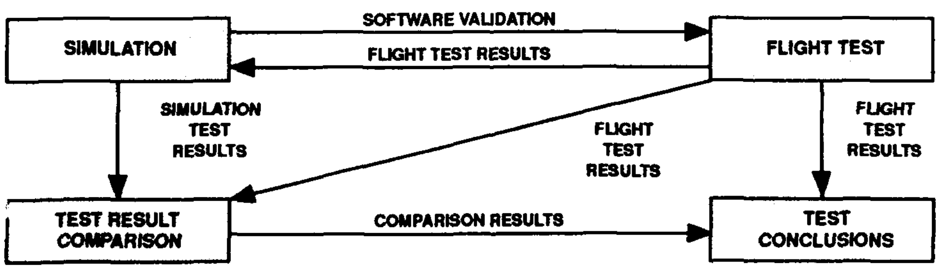

FIGURE #2: TEST PROCESS FLOW CHART

Once the flight control anomaly had been well characterized, a control law modification had to be developed to eliminate this problem. It had been determined that the severity, as well as the probability of occurrence, of an oscillation was a function of dynamic pressure. Pitch oscillations with an average amplitude of 6 g's had been obtained with simulation at a dynamic pressure of 550 lbs/sq-ft. The control law pitch integrator was modified to reschedule the total pitch command available as a function of dynamic pressure. As dynamic pressure increased, the maximum pitch command available was reduced to eliminate any possibility of horizontal tail rate limiting.

When the final version of the modification had been decided upon, the simulator once again proved vital in validating and optimizing the proposed modification. Ground simulation tests, using the modified control laws, were accomplished that validated the fix prevented pitch oscillations from occurring. It was then demonstrated that the software fix terminated oscillations, induced with the original control laws, once the modified control law path was selected.

Next the modified control laws were tested, using simulation, to ensure that the fix was effective throughout the entire flight envelope in all types of DFLCS modes and aircraft configurations.

The digital backup mode (DBU), air-to-air gain schedule, air-to-ground gain schedule, cruise configuration (CR) and power approach configuration (PA) were all tested with the new control law modification.

Of equal concern was the possibility of aircraft performance degradation due to the new total pitch command schedule. This was a valid concern because the maximum available pitch command was reduced and directly influenced the aircraft pitch performance. The control law modification was then aggressively tested on the simulator to ensure that the aircraft performance was not degraded when compared to a production aircraft. Simulation tests showed that the fix was effective throughout the entire flight envelope and did not degrade the aircraft performance.

Once the test team was satisfied that the fix was validated and optimized for flight test, a flight control computer was retrofitted with the software modification and bench tested. This process involved a complete test of the fix during multiple failure modes to ensure that the software modification had been correctly implemented. Next the modified flight control computer was linked to the aircraft manufacturer's ground simulator and further tested with a test pilot in the cockpit. These tests all proved successful and the next step was to flight test the flight control law modification.

FLIGHT TEST PREPARATION

Prior to actual flight testing of the fix, a test plan had to be developed. With the help of simulation, the test point maneuvers and flight conditions were selected. A range of airspeeds and altitudes were chosen to duplicate the actual incident and also provide an adequate safety margin for recovery. A variety of maneuvers were selected to test the effectiveness of the fix as well as determine if aircraft performance had been sacrificed.

Other flight test preparation work included emergency procedure development in the event of an oscillation during flight test. Previous simulation tests had determined that reducing airspeed damped an existing oscillation. Thus, retarding the throttle and deploying the speed brakes was chosen as the pilot action in response to an oscillation. Additionally, the DBU software was a secondary flight control mode with reduced gains and included a horizontal tail rate limiter. Ground simulation demonstrated that an oscillation could not be excited in the DBU mode. Therefore, a second course of action would be to select DBU if airspeed reduction failed to terminate the oscillation. However, during a severe oscillation DFLCS failures were possible and this course of action was only recommended if no DFLCS failure lights were illuminated.

Another advantage of ground simulation was accomplished through pilot training sessions. These exercises familiarized the pilots with the test maneuvers they would be required to perform during flight test as well as the necessary emergency procedures to recover the aircraft.

TEST RESULTS

Flight Test Results

Flight tests were conducted on a production fighter aircraft with a DFLCS. The test aircraft configuration and gross weight was kept consistent with the TAC aircraft

that experienced the pitch oscillation for test validity. The test points flown were designed to either assault the modified total pitch command schedule or evaluate the aircraft performance. The pitch command schedule assault maneuvers included both types of maneuvers described earlier that excited the oscillation during ground simulation tests. The aircraft performance checks consisted of maximum command pitch and roll performance maneuvers, target tracking exercises, and basic fighter maneuvers.

No pitch oscillations were encountered during the conduct of the flight test program. It was also demonstrated that the aircraft performance had not deteriorated due to the modified flight control laws because the rescheduled pitch command limits were not exceeded.

Test Result Comparison

A recorded aircraft data tape containing pilot inputs, control surface deflections, and aircraft flight path angles and rates was used for a comparison of simulation results with flight test results. The flight test recorded pilot inputs were fed into the simulator and the resulting simulated control surface deflections, angles, and rates were recorded. These time histories were then compared with the flight test time histories.

Two important conclusions can be drawn from this comparison. The first conclusion would involve determining if the pilot had executed the proper control stick inputs during flight tests to excite an oscillation. The second conclusion would be to determine the accuracy of simulation predictions of flight test results with the modified flight control laws.

To answer the first question, the recorded pilot inputs were fed into the simulator, with the fix deactivated, and a sustained pitch oscillation was obtained (Figure #3). From these results, it was determined that the pilot inputs would have excited a pitch oscillation if the fix had not prevented it.

To address the second question, the pilot inputs were once again fed into the simulator, this time with the fix activated, and the simulated time history was compared to the flight test time history (Figure #4). The time history comparisons were almost identical in frequency and phase, which demonstrated that the simulated aircraft responses had been modeled correctly. However, the predicted magnitudes of the aircraft responses were slightly higher, –i.e. more conservative, than the actual flight test results. These discrepancies in magnitude could be attributed to inaccurate aerodynamic and engine thrust data contained in the simulator data base. The aerodynamic data is based on an earlier model of fighter aircraft and does not account for configuration changes in the subject aircraft model. The engine thrust deck is also not updated with the correct thrust data. However, given this small error, these comparisons show that the simulator fairly accurately predicted the flight test results of the modified flight control system.

CONCLUSIONS

This type of flight control problem, aircraft control surface rate limiting, could never have been investigated or defined without the use of ground simulation because of insufficient data. Simulation provided the necessary tools to solve the puzzle and develop a simple solution for the user. Simulation tests accomplished the preliminary work necessary to commence flight test by developing and validating a software modification that proved successful in flight test. Ground simulation also prepared the project pilots for the flight test program by providing the opportunity for practice of test point maneuvers and emergency procedures. Flight test was then utilized to further validate the flight control modification and ensure that the aircraft performance was not degraded.

Finally, the results from both simulation and flight test were analyzed and conclusions were drawn from this comparison. Simulation results confirmed the quality of the flight test maneuvers. A pitch oscillation would have occurred during flight test if the modified flight control laws had not been implemented. Alternately, flight test results demonstrated that the simulation predictions had been correct. The flight control modification performed as predicted and no oscillations were encountered during flight test. Based upon these results, the AFFTC concluded that the simulation and flight test program was a success.

Subsequently, a solution to a potentially dangerous flight control problem was discovered, validated and retrofitted into the USAF fleet of fighter aircraft equipped with a DFLCS due to the invaluable technical support of ground simulation used in conjunction with flight test.

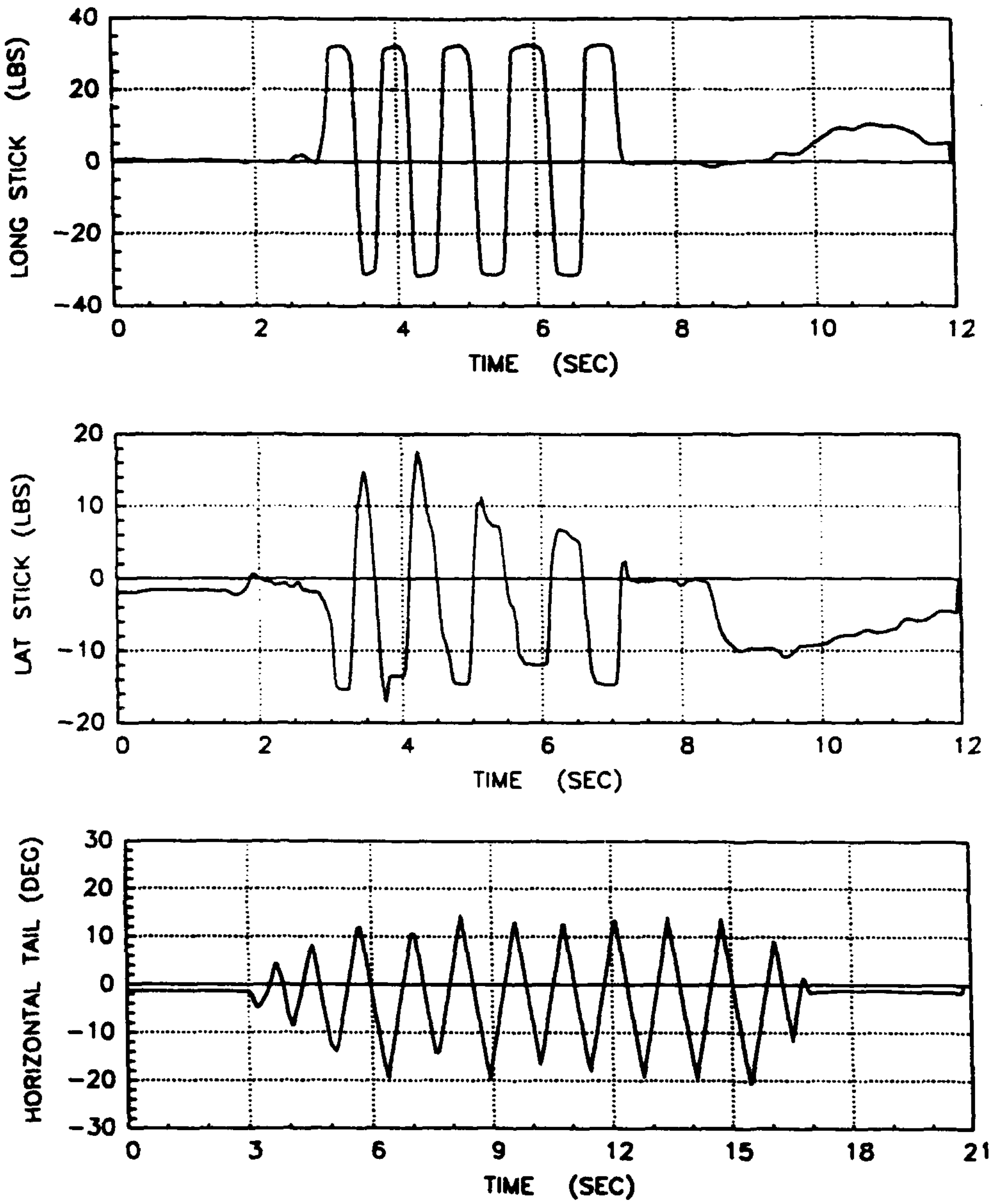

FIGURE #3: SIMULATED PITCH OSCILLATION

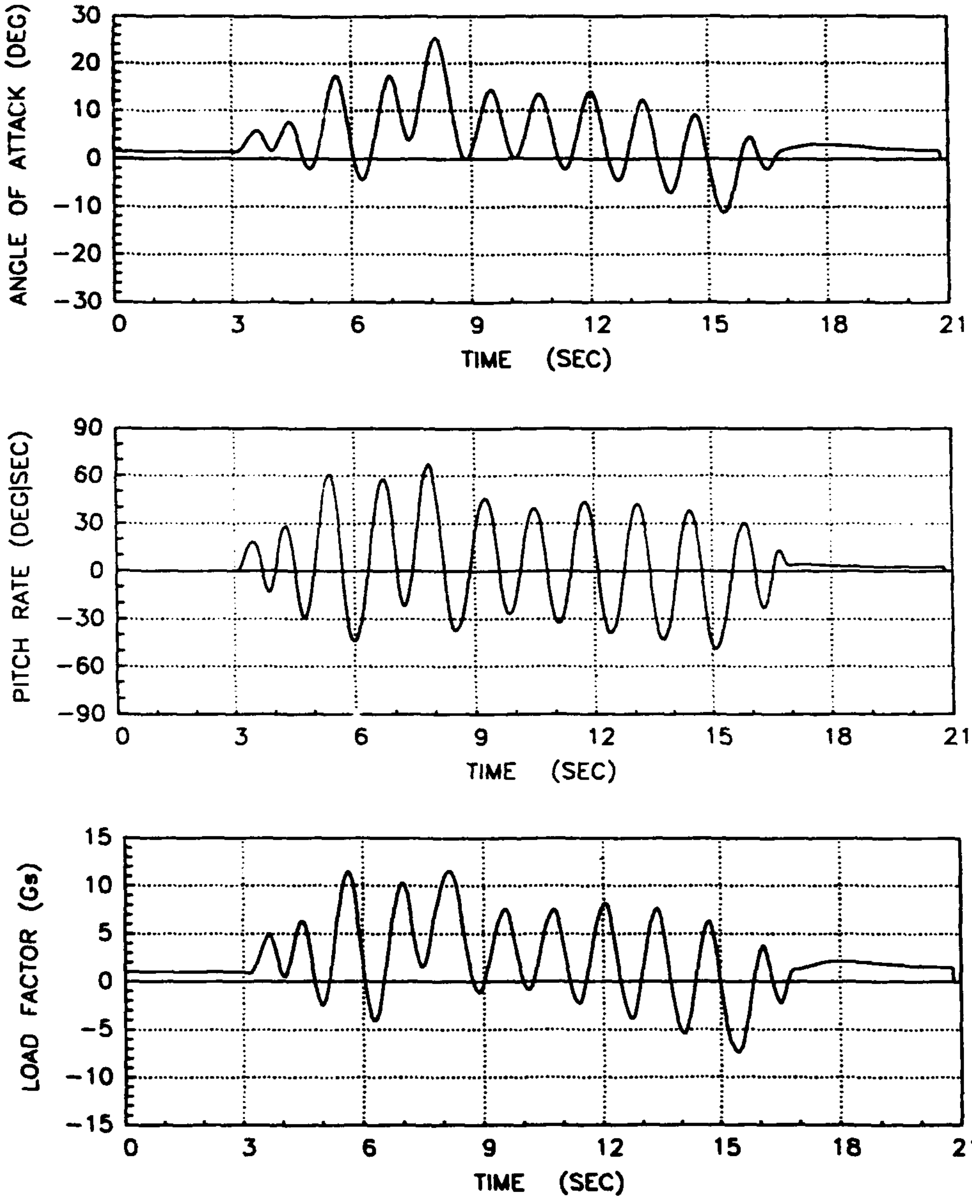

FIGURE #3: SIMULATED PITCH OSCILLATION (CONCLUDED)

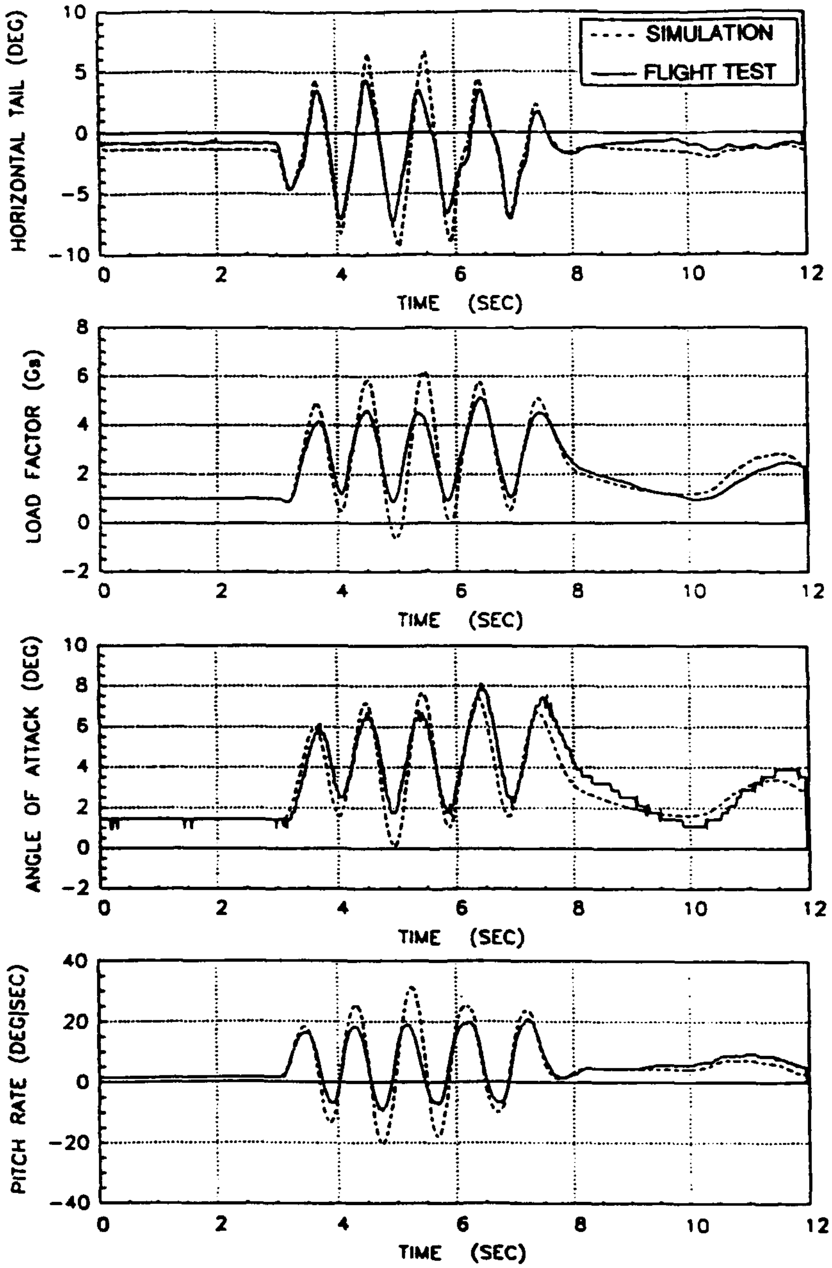

FIGURE #4: TIME HISTORY COMPARISON

FLIGHT SIMULATION AND DIGITAL FLIGHT CONTROLS

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France

Abstract

The A320 is the first civil airliner to make extensive use of digital flight controls. Despite previous experience in this technological field, development of this system in a short time schedule has been a challenging issue. Simulation under its various forms, including simulators with a very high level of integration of actual aircraft components, have played a key role in the successfull achievement of the Flight Control development process. It has allowed a better overall system quality to be achieved by the extension and thoroughness of testing performed : some 18 000 hours of simulator testing were logged at the time of A320-200 certification. Simulation has also proved to be a perfect complement to flight testing which today still remains the definite way to validate a Flight Control System and associated Handling Qualities : by increasing the safety and effectiveness of flight testing, simulation has participated in the overall development cost and programme monitoring.

In the field of simulation used for airline training purposes, the introduction of digital flight controls has moved the representativity-critical areas from aerodynamic model accuracy to Flight Control System representation exactness. Aerospatiale is convinced that use of actual aircraft Flight Control computers is needed to guarantee fully the degree of fidelity consistent with the standard of training quality offered today. Simulator acceptance procedures had also to be adapted to address the case of closed loop controlled aircraft correctly.

1 . Introduction

European experience in fly-by-wire application to civil airliners is now some 20 years old. More recently, entry into service of the A320 has provided a major milestone in this technical challenge.

In the same period of time, simulation has benefitted from great improvements in computer power, model accuracy and environmental fidelity. It is now widely used in both training and development fields.

The objective of this lecture is to show how these two concepts : Digital Flight Controls and Simulation, have been intermixed in the case of both development and operation of a fly-by-wire civil airliner like the A320.

2 . Digital Flight Controls : A320 experience

2.1 . Previous experience

The decision to make extensive use of fly-by-wire was not taken without considering the experience acquired in this field :

- since 1969, Concorde has been flying with a three axis full authority analog flight control system with a mechanical back-up on each surface,
- in 1978, an experiment was conducted on Concorde 01 involving the use of a sidestick, a C* type of control law and a digital computer,
- in 1981, the concept of "Forward Facing Crew Cockpit" was introduced in the Airbus A300B4 programme ; this involves a digital dual-dual autopilot system (two computers, each with a Command and a Monitor channels),
- Airbus A310 and A300-600 have their spoilers, flaps and slats controlled by digital computers,
- in 1983 and 1985, extensive flight testing was performed on A300B S/N 3 modified to embody sidesticks and A320 type control laws.

2.2 . Brief survey of A320 Flight Control System

2.2.1 . Aerodynamics

The A320 is fairly conventional in this respect and early design did not take credit of fly-by-wire ; the tailplane and fin are therefore of usual size ; natural modes are damped throughout the flight envelope and CG range, and the maneuvering margin is still positive at the most rearward CG position.

Primary flight controls make use of the following control surfaces :

- a one piece rudder,
- a Trimmable Horizontal Stabilizer fitted with two mechanically independent elevators,
- two ailerons and ten upper wing surfaces.

2.2.2 . General architecture

All control surfaces are hydraulically activated through the three independent general supplies of the aircraft. All surfaces are electrically signalled. The roll axis and elevators have a purely electrical control. The THS and rudder have a mixed electrical/mechanical control so that the A320 can still be flown and kept under control in the case of a momentary complete electrical failure.

As the pilot's main pitch and roll controls are free of mechanical links, they are advantageously achieved by sidesticks. Their lack of mechanical synchronisation is replaced by a priority logic and announcement system.

The electrical Primary Flight Control System relies on the use of seven digital computers :

- two ELACs which provide Elevators, Ailerons and THS control. ELACs compute the normal control laws for all axes,
- three SECs which provide Spoiler, Elevators and THS control. The SECs are only capable of computing reconfigured control laws,
- two FACs which provide Rudder control through yaw damper actuators ; the FACs also compute the characteristic speeds, rudder travel limitation and rudder trim control.

The electrical supply to the Flight Control System comes from the two general AC and DC n° 1 and 2 systems fed by the two engine driven generators. In the case of failure or unserviceability, the two supplies can be taken over by the APU generator or the Ram Air Turbine. In addition, two batteries with a minimum endurance of 30 minutes provide a permanent back up supply.

2.2.3 . Flight Control Laws

One of the positive outcomes of Fly-By-Wire is to allow elaborate flight control laws to be introduced : conventional direct (linear) relationship between pilot's controls and surfaces is replaced by computations which interpret the pilot's input as a request for a given aircraft response and deflect the surfaces accordingly until the feedbacks indicate that the desired response

has been obtained.

In pitch, the A320 makes use of the C* law which is basically a load factor demand type of control law : once the stick is released, the aircraft is forced to a one g flight, corrected for pitch and bank attitudes. As a consequence, the control law automatically provides the elevator deflection necessary to cope with turbulence, speed changes, CG effect, trim changes associated with thrust and high lift/airbrakes operation. From the pilot's point of view, corrective pulse inputs are just needed to correct attitude, and the aircraft benefits from auto-trim characteristics ; it displays neutral static stability and positive platform stability. When the stick is fully deflected, the load factor demand is automatically limited to an extent consistent with the structural design capability.

For the lateral axis, the sidestick deflection is treated as a roll rate demand and roll and yaw control surfaces are deflected in order to provide good turn coordination (sideslip minimization) and comfortable dutch roll damping. In the same way as on the pitch axis, the bank angle is corrected by pilot's pulse inputs ; the aircraft displays neutral spiral stability and positive bank stability with respects to turbulence. When the stick is fully deflected, the roll rate is limited to 15°/s which has been found to be good compromise between adequate maneuvering capability and margin relative to Pilot Induced Oscillation tendency (roll rate is not reduced when the aircraft is responding to turbulence). In the case of engine failure, even with no reaction from the pilot, the control law will stop the roll rate and stabilize the aircraft at a moderate bank attitude and slowly diverging heading.

Protections : while neutral static and spiral stabilities greatly improve the comfort of piloting in the usual operational envelope, they are inherently removing the cues that indicate the departure from these usual flight conditions on conventional aircraft. Therefore, protections have to be introduced when the aircraft reaches the boundary of the peripheral flight envelope :

- in pitch :

  - strong positive static stability is provided beyond VMO/MMO, reducing the maximum speed excursion in the case of diving upsets,
  - strong positive incidence stability is provided at low speed, reducing the maximum achievable angle of attack below the stalling incidence (Angle of Attack Protection),
  - pitch attitude is limited between the practical values of - 15°/+ 30°.

- in roll :

  - strong positive spiral stability is provided beyond 33° bank angle ; maximum achievable bank angle is limited to ±67°,
  - maximum bank angle is further reduced when the aircraft is operating into either Angle of Attack Protection or High Speed Protection.

Reconfigurations : correct computation of the above control laws relies on the availability of consistent separate sources of feedback information as well as minimum number of control surfaces and computers. When these conditions are no longer satisfied, normal control laws are progressively reconfigured to downgraded modes according to the level of remaining available items. Reconfigurations only take place after double failures. The most downgraded level is achieved when the control laws have reverted to direct type.

2.2.4 . General precautions

Owing to the criticality of the flight control system, the following safety objectives have been set :

- definitive loss of roll control : Extremely Improbable,
- runaway of THS or elevators : Extremely Improbable,
- definitive loss of elevators : Extremely Remote.

In addition, the following maintenance objectives have been selected :

- take-off allowed with any one Flight Control computer failed,
- take-off allowed with one aileron or one spoiler or one THS motor failed,
- no special daily test or special test equipment,
- "Bite" system to identify the failed LRU.

These objectives have lead to the above mentioned system architecture. The following precautions and/or features also contribute to overall achievement of the objectives :

- Level 1 type software as defined by DO178,
- dissimilar redundancy between SECs and ELACs, between COM and MON channels,
- wire routing tolerant to mechanical failures of the structure,
- passive Electro-Magnetic Interference and Lightning protections,
- multimode electrically signalled hydraulic servojacks : active mode, damping mode, self centering mode.

3. Contribution of Simulation to Flight Controls System development

Now we reach the essential part of the presentation. In order to have a better understanding of the stakes involved, it is worth recalling the tight timescales that were put on the A320 programme:

programme launching	:	early 1984
first flight	:	February 1987
European certification	:	February 1988
Entry Into Service	:	March 1988
FAA certification	:	end of 1988

Despite previous experience relative to Fly-By-Wire, the extent of its application to the A320 coupled with the above timescales made the development phase a tough and challenging experience in which simulation played a key role.

3.1 . Simulation tools

3.1.1 . "Batch" type simulation codes

A modular system of codes and subroutines, called OSMA (for Outil de Simulation du Mouvement de l'Avion) has been extensively used for general Handling Quality studies as well as flight control laws tuning in non linear domains. It is worth noting that aerodynamic, propulsive, flight mechanics models and subroutines are the same as those used and supplied to the training simulators within the Data Packages.

3.1.2 . "Development" simulator

This simulator is fitted with a fixed faithfull replica of the A320 cockpit and controls and a visual system ; it was put into service as early as mid 1984, as soon as a set of previsional A320 aero data, based on wind tunnel tests, were made available. The

Flight Control System was at this stage fully simulated. The development simulator was used to develop and initially tune all flight control laws in a close loop cooperation process with Airbus Industry flight test pilots.

3.1.3. "Integration" simulators

Three "Integration" simulators were put into service in 1986. They include the with fixed replica of the A320 cockpit, a visual system (for two of them), and a lot of actual aircraft equipment including computers, displays, control panels, warning and maintenance equipment ; one of them, called S1, is even coupled to the so called "Iron Bird" which is a full scale replica of hydraulic and electrical supplies and generation and is fitted with all the actual Flight Control System components including the servojacks. The main purpose of these simulators is to test the operation, integration and compatibility, and the process of interactive communication between the computers in an environment closely akin to that of an actual aircraft.

3.2. Contribution of simulation to system quality

The quality and associated safety and reliability of operation, of a critical system like the Digital Flight Control, mainly relies on a two step process :

- quality of the specification,
- quality of software and complete consistency between software and specification.

The latest step is guaranteed through the use of the very stringent rules associated with "Level 1" software. These rules issued by the Certification Offices and supplemented by the own manufacturer's or vendor's rules (based on experience), theoritically ensure that the software embodied in the Flight Control System computers is strictly consistent with its specification.

Today the first step is still somewhat less formalized and more difficult to assess fully : how can it be guaranteed that the specification on which the software is based fullfills all the performance objectives and offers the adequate functioning in every forseeable configuration of the environment of the system ? In this area, simulation provides for an invaluable tool for analysis or checking of huge numbers of potential cases or combination of cases which are obviously out of the scope of flight testing ; for example, parameters like weight, center of gravity location, altitude, speed (inside and outside the normal flight envelope), aircraft configuration, wind, turbulence (including windshear) have been systematically covered by simulation at every major step of the Flight Control System design. We may even say that, owing to the considerable number of inputs to the system (several hundreds), checking all the combinations of these inputs, if they were considered to be independent, would be practically inaccessible even by simulation. In this respect, a good simulator providing faithful simulation of all these inputs to the system as well as overall aircraft behaviour, allows for a significant reduction of the number of potential cases to be analysed : all inputs are no longer fully independent parameters and combinations which are not possible are automatically eliminated.

Even if the nominal functioning and operation of a civil airliner already provides for a wide scope of various environmental conditions, the abnormal operation is still more complex. The A320 simulators have been extensively used to develop and check all the logics embodied in the Flight Control System specification which should malfunctions occur, either enable nominal operation of the system to be maintained or reconfigure the system to a level of performance geared to the resources resulting from the malfunction. Areas of particular interest in this respect include :

- runaway of inputs from other systems (ADCs, IRSs, ...)
- oscillatory failures
- mechanical failures (jamming, disconnection)
- electrical supply transients
- effects of lightning induced disturbances
- effects of Electro Magnetic Interference induced disturbances.

A thorough assessment of system behaviour in the case of the abovementioned abnormal conditions is clearly inaccessible by pure analysis or by flight testing.

3.3. Contribution of simulation to safe and cost-effective flight testing

Flight Testing indoubtedly remains the ultimate and indispensable way of validating a flight control system. With the current state of the art in simulation, simulators cannot yet fully take the place of flight testing for Handling Quality assessment, especially for close to the ground phases of flight. On the other hand, A320 simulators have certainly made flight testing both safer and more productive. Anyway, safer flight testing also means a more cost effective development process when taking the short timescale and the cost of the machines into account, not to mention the detrimental advertizing arising from any incident.

Here are some examples which illustrate how simulators have proved to be perfect complements to flight testing in an overall cost-effective objective :

- flight crew training before first flight (self evident),
- reduction of the scale of test programme : prior selection on a simulator allows the most significant scenari to be selected,
- aircrew familiarisation in the case of tricky test successions (also self evident),
- systematic test on the integration simulators of any new version of software ; this test was mandatory before any new version of Flight Controls computer was allowed to be fitted on a development aircraft for flight testing,
- debugging in the case of unexpected failure during flight testing : by back playing the conditions of the incident, varying the suspected parameters or locally increasing the scale or sensitivity of the instrumentation, a detailed set of facts can rapidly be built up which allow the anomaly to be traced quickly and corrected with a minimum delay in the flight test programme,
- simulator use in place of flight testing for very severe or critical failures ; despite the introduction of this paragraph, some very severe failures have been tested on the simulators only ; this is the case when the probability of such failure or combination of failures allows hazardous or even catastrophic consequences according to the certification requirements ; this was also the case whenever the aircraft, volontarily forced in this failure state, became particularily vulnerable to an additional unexpected failure.

3.4. Side contribution of simulators

Although far from their fundamental purpose, A320 simulators have also been something of a showcase for know-how. Many demonstrations have been performed on these simulators, to the benefit of customers (confirmed and potential), representatives of government agencies, various VIPs, etc ... Especially before the first flight or first roll out of production aircraft, simulators were one of the visible and tangible back ups to the confidence necessary to initiate or confirm the involved investments.

4. Training Simulators of Digital Flight Controlled Aircraft

4.1. Airbus worksharing

In the Airbus Industrie organization, the French partner, Aerospatiale, is in charge of the Flight Control System, cockpit design, general Handling Qualities assessment and certification, engine/airframe integration and aerodynamic data release.

This naturally leads to an additional task, for which

Aerospatiale is also responsible : gathering, formating, issuing and supporting all the information and equipment that are needed to build, check and certificate the training simulators of Airbus aircraft.

Over the past decades, the significant improvement in training simulator fidelity as well as their generalized use in the training cursus have played an unarguable role in the overall improvement of air travel safety. Good training is as important as well designed aircraft and good simulators are a must for achieving good training. What is the impact of digital flight controls on training simulators ? Here is Aerospatiale's experience-based opinion.

4.2 . Importance of Flight Control System representation

On a conventionally controlled aircraft, moving surface deflections are directly linked to pilot's control positions. Therefore, simulation of this part of the Flight Control System is straight forward and fidelity of simulator behaviour mainly relies on the accuracy of the aerodynamic model. But a good simulator must also provide whenever possible the most faithful cues. Control forces are among these cues ; in the case of mechanical control through cables and rods, hydraulically powered or boosted surfaces, including artificial feel and stall warning devices, the correct simulation of control forces is not an easy task. From an Handling Quality point of view, the two critical areas of a conventionnally controlled aircraft simulator are the aerodynamic model and the control force model ; acceptance tests of a training simulator, both for customer and certification, have a content in accordance with these areas of criticality.

On a digitally controlled aircraft, the behaviour of the aircraft, as felt by the pilot, is mostly affected by the Flight Control System ; the flight control laws, owing to their robustness and the feedbacks taken into account, make the behaviour even less sensitive to the aerodynamic model. Therefore, the critical area of a digitally flight controlled aircraft simulator is that of the Flight Control System representation ; criticality of the aerodynamic model only becomes significant for reconfigured modes, when these modes reproduce the direct type of control of todays' conventional designs.

4.3 . Simulation versus stimulation

All A320 training simulators are equipped with actual aircraft sidesticks ; this guarantees the fidelity of pitch and roll control forces without any further need for check or proof of match.

Early A320 training simulators were fitted with simulated Flight Control computers, because it was impossible to have the relevant aircraft computers available for training simulators in time and in sufficient number. In this case, the software embedded in the seven computers was carefully analysed and selectively compacted.

Now that the production run of ELACs, SECs and other computers does allow some sets of them to be allocated to training simulators, Aerospatiale is strongly in favour of the so-called "stimulation" option : in this option, training simulators are equipped with the actual aircraft computers, as opposed to a simulation of them. By the way, "stimulation" is already the only available option for Flight Management Systems of many current conventional aircraft.

Here are the reasons for Aerospatiale's position :

- criticality of Flight Control System representation for achieving effective training,
- difficulty to define criteria for simplified simulation of the Flight Control System : it is difficult to limit the actual use of a training simulator strictly to its validity domain ; risk of negative training in the case of uncontrolled use outside this validity domain,
- it is almost impossible to check the simulation of such a complex system thoroughly ; use of "Level 1" software rules to derive simulation software from the detailed specification of the computers is practically out of the reach of training simulators manufacturers or would be too costly. Validation of the simulation option relies on a sample set of test cases on which to base a general level of confidence in the overall simulation model,
- lengthy updating process leading to a simulator standard which is often beyond that of the airline fleet ; risk of a loose updating process monitoring,
- good compatibility of Flight Control computers with the specific operational use on a training simulator (repositioning, freeze...) and the injection of failures, without the need for computer modification.

For upcoming programs like the A340/A330 or the A321, Aerospatiale has decided to rationalize and improve its support to the training simulator community by only allowing the stimulation option.

4.4 . Training Simulator acceptance procedures

Acceptance of a training simulator is performed at two levels : by the customer (airline or training center) upon taking delivery and by the Airworthiness Authorities before allowing credit to be given for the training performed on the machine. The amount of testing needed for Certification is generally less extensive than (and included in) the list of tests used for customer acceptance.

In both cases, the list of tests used on simulators of conventionally controlled aircraft have been found inappropriate for a simulator of a digitally controlled aircraft :

- they were unnecessarily concentrating on control forces (useless when the sidestick is an actual aircraft component),
- they were not addressing specifically the case of a closed loop control aircraft.

Therefore, Aerospatiale has developed this opinion to the Airwothiness Authorities who were very receptive ; a working group has been set up including some airlines and simulators manufacturers as well. The outcome was a better alternative set of validation tests proposing a two step validation process :

- first step : validation of the aerodynamic model only (response of the aircraft to control surface position) ; once performed, conclusions remain valid whatever control law (normal or reconfigured) is active or after any modification/updating of the Flight Control system,
- second step : validation of the Flight Control system representation through complete, closed loop aircraft response ; the amount of these tests is intended to cover the most demanding simulation option and could be reduced in the event of the stimulation option being selected.

This acceptance procedure is now currently used to certificate all in service A320 simulators.

5 . Conclusion - A glimpse into the future

After relating the role played by simulation in the development process of the A320 Digital Flight Control System as well as the impact of this system technology on training simulators, this lecture can be concluded by a glimpse into the future :

Simulation will play an ever-increasing role in the development process in order to reduce cost and timescale by achieving the best definition at the earliest stage of development. Right now for the A340/A330 programmes, engineers in charge of flight control law design can test within minutes the control laws they have just specified on one of the design office simulators made of a console with main controls (joystick, thrust levers, controls for rudder, airbrakes, slats and flaps...), a video screen with a replica of the Primary Flight Display, Autopilot Command Unit and display of controls surface position, recording and plotting facilities, all linked to a host computer with full aerodynamic, engine, ground roll and Flight Control System modelizations. At the same time, engineers in charge of system architecture and computer logics benefit from a complete simulation of all software embedded in the five computers of the A340/A330 system ; this simulation is used to verify all reconfiguration logics as well as the dialogue between computers. Both simulation facilities are available well before any computer prototype is produced. They strongly rely on generalized digitalization methods that include computerized specification of

both flight control laws and logics, followed by automatic generation of the associated simulation software.

In the training simulator area, sophistication and interrelationship between digital systems including Flight Controls will lead to an increased use of actual aircraft equipment as a guarantee of simulator representativity : from the already stimulated FMS to Flight Control computers, Autopilot computers and even critical components in procedures training such as Flight Warning Computers. This tendency will only be reversed when the software embedded in these computers is made compatible and transportable without alteration onto simulator host computers sized to accept them all without truncation.

THE APPLICATION OF FLIGHT SIMULATION MODELS IN SUPPORT OF ROTORCRAFT DESIGN AND DEVELOPMENT

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ABSTRACT

McDonnell Douglas Helicopter Company 's overall approach to design development and flight evaluation through flight simulation models is presented. Flight simulation model description, validation against flight test database, and applications for rotorcraft design and development, are presented. Specific model refinements for each application are emphasized. Examples include power-off emergency landing, empennage design, maneuver envelope expansion, engine-airframe integration, and manned simulations.

NOMENCLATURE

A_{1S}	lateral cyclic pitch
B_{1S}	longitudinal cyclic pitch
B	rotor blade tip loss factor
C_H/σ	disc longitudinal force coefficient
C_Q/σ	torque coefficient
C_T/σ	disc thrust loading coefficient
C_Y/σ	disc lateral force coefficient
I_E	engine moment of inertia
I_G	nose gear moment of inertia
I_R	main rotor moment of inertia
I_{TR}	tail rotor moment of inertia
N/q	fuselage yawing moment coefficient
M/q	fuselage pitching moment coefficient
M_{qq}	modal generalised mass
Q_q	modal excitation force
Q_R	main rotor torque
R/q	fuselage rolling moment coefficient
V_A	total air speed
X/q	fuselage drag force coefficient
Y/q	fuselage side force coefficient
Z/q	fuselage lift force coefficient
a_{1C}	longitudinal flapping in C-Frame
a_z	aircraft normal acceleration
b_{1C}	lateral flapping in C-Frame
i_{HS}	horizontal stabilator incidence
p_B, p	helicopter roll rate in B-Frame
q_B, q	helicopter pitch rate in B-Frame
r_B, r	helicopter yaw rate in B-Frame
u_B, u	aircraft longitudinal velocity, B-frame
v_B, v	aircraft lateral velocity, B-frame
w_B, w	aircraft normal velocity, B-frame
α	blade angle of attack
β	flap degree-of-freedom
γ	Lock number
ζ	modal damping coefficient
$\Delta\psi$	rotor asimuth increment
ΔT	multi-rate sampling time
η	lead-lag degree of freedom
θ	helicopter trim pitch attitude
$\vartheta_{3/4R}$	main rotor collective pitch @ 3/4 radius
θ_s	main rotor shaft angle longitudinal tilt
λ_C	total axial flow in C-Frame
λ_i	induced axial flow
λ_S	total axial flow, S-Frame
μ_X	longitudinal advance ratio
μ_Y	lateral advance ratio
μ_C	axial flow ratio, C-Frame
σ	main rotor solidity
ϕ	helicopter trim roll attitude
χ	main rotor wake skew angle
ψ	helicopter trim heading
ψ_R	reference blade asimuth position
Ω_E	engine degree-of-freedom
Ω_R	main rotor degree-of-freedom
Ω_{DT}	drive train degree-of-freedom
$\bar{\Omega}_R$	effective yaw rate in R-Frame, $(\Omega_R - r_r)$
Ω_{TR}	tail rotor degree-of-freedom
ω/Ω	modal frequency parameter
τ_β	flapping time constant

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1. INTRODUCTION

Application of flight simulation models for design and development of rotorcraft offers several major benefits. It provides a cost-effective means to evaluate helicopter handling qualities during design before substantial resources are committed to a program for full

scale development. Simulation support for flight test during a helicopter development can result in significant cost savings. In addition, design of unconventional configurations, such as tilt wings, tilt rotors, and those with advanced anti-torque systems or auxiliary propulsion systems, often require demonstration of proof-of-concept in manned simulators before a prototype is built. Furthermore, handling qualities assessment of future rotorcraft designs through simulation to evaluate competing designs is becoming increasingly important, demonstrated recently by the U.S. Army's Light Helicopter selection process. Application of flight simulation models therefore plays an important role in rotorcraft design and development.

Most of the flight simulation codes that exist in the helicopter industry today have had their beginnings through simple applications during the development stage of a rotorcraft project. The McDonnell Douglas Helicopter Company's (MDHC) flight simulation code had its beginning when it was required to simulate a power-off emergency landing procedure for a OH-6A Cayuse helicopter. There has been several applications within MDHC since then, including the AH-64A Apache empennage redesign, piloting techniques for terrain avoidance maneuvers, air-to-air combat flight envelope expansion, advanced flight control law development, and flight test support for engine/airframe integration for the AH-64A Apache upgrades. Most of the simulation applications have contributed to both model refinement and validation. MDHC's flight simulation model is also being used in several manned simulators for a variety of applications.

MDHC's flight simulation code has been progressively developed over the past fifteen years. It is based on a comprehensive mathematical modeling approach. The flight model and code have been validated against several flight test databases for a variety of maneuvers and flight conditions, both through dedicated validation efforts and specific applications.

An overview of the MDHC's flight simulation code, description of the mathematical model, results of validation against flight test database, and selected applications of the flight model for rotorcraft design and development, are presented in this paper.

2. FLIGHT SIMULATION CODE AND MODEL DESCRIPTION

2.1 Overview of the Flight Simulation Code

McDonnell Douglas Helicopter Company's flight simulation code, referred to as FLYRT, has been in a continuous state of development over fifteen years. A description of the FLYRT code and its application for rotorcraft design and development was first presented in ref. [1]. A detailed documentation of the most recent version of the FLYRT code is presented in ref. [2]. The name FLYRT identifies collectively the group of computer codes that form the flight simulation code. The code consists of a main executive called APFLITSIM (Flight Simulation), which supervises the sub-executives TRIMEX (for Trim), APLINMOD (Linear Model generator), and FLYRT (for Fly). Organisation of the FLYRT code for trim/linear perturbation model generation and for "fly" procedures are illustrated in figures 1 and 2, respectively.

The TRIMEX sub-executive, shown in figure 1, calls the main rotor, fuselage, horizontal tail, anti-torque, and landing gear modules to generate the forces and moments acting at the aircraft center-of-gravity. During trim, the vehicle model is constrained to steady flight in a specified configuration, with the time integration sequence inoperative. The body acceleration vector is driven systematically to zero to achieve a trimmed state. Several trim options are provided in the code including trim at zero sideslip, ball centered, at fixed collective, on the ground, and in autorotation.

An option for generating a linear perturbation model about a trimmed state is available through the APLINMOD module. The conventional set of eight-states (u, w, q, θ, v, p, r, and ϕ) with six degrees-of-freedom is adopted in generating such a model. The control parameters used are $\vartheta_{3/4R}, A_{1S}, B_{1S}, \vartheta_{T/R}$, and i_{HS}.

The FLYRT sub-executive, illustrated in figure 2, is organised to simulate specific flight maneuvers initiated from a trimmed state. In the nonreal-time "fly" mode, FLYRT uses a "paper pilot" software device to execute a wide range of specified maneuvers. The paper pilot combines application of prescribed flight control inputs with an adaptive control system to simulate the pilot actions. A subroutine is created for each maneuver to be executed to generate the prescribed control inputs. The pilot actions, along with the aircraft state, drive the flight control system module to generate the total control settings for the flight model components.

The equations of motion module (EOFM) in the fly mode calls, in addition to the component modules called in trim, the engine module to return the engine torque, sums the forces, and executes solution of coupled body/drive train equations to compute the acceleration vector. Time integration is performed in a separate module to compute the velocity and position vectors in the Earth-frame. Euler angles are computed in quaternions which eliminate singularities and thus enable execution of aerobatic maneuvers such as loops and rolls.

The aircraft components modeled in FLYRT are: main rotor, fuselage/wing, horizontal tail, and anti-torque systems, which are generic models, and landing gear, engines, and flight control system, which are aircraft specific models. Descriptions of the component models and their salient features are presented next.

2.2 Main Rotor Models

The main rotor model, being the most important

part of any rotorcraft flight model, has undergone extensive development at the McDonnell Douglas Helicopter Company. The main rotor module in FLYRT has three options, with increasing levels of complexity. They are:

1. A linear analytical model.
2. A hybrid (rotormap) model.
3. A blade element model.

2.2.1 Linear Analytical Model

In the linear main rotor model, the four components of the hub generalised forces (blade loading or thrust coefficient, longitudinal and lateral in-plane force coefficients, and shaft torque coefficient) are calculated as functions of $\vartheta_{3/4R}$, μ_C, and λ_C, where μ_C and λ_C are in the control frame of reference. The hub rolling and pitching moments generated by the rotor blade are centrifugally transmitted to the body through the flapping hinge and are computed as a function of the lateral and longitudinal flapping angles. The closed form analytical expressions for the forces and moments of the linear rotor model are obtained as the linear solution of a nonlinear rotor model, ref. [3]. The linear main rotor model is used mainly for preliminary design support.

2.2.2 Hybrid (Rotormap) Model

The hybrid model consists of a quasi-static rotormap, generated off-line, and closed form analytical solutions to account for the transient effects. The rotormap consists of a table of a six-state vector (rotor thrust, shaft torque, longitudinal and lateral in-plane forces, and longitudinal and lateral cyclic flapping angles) as a function of the performance parameters $\vartheta_{3/4R}$, μ_C, and λ_C.

The rotormap database is generated based on a nonlinear blade element model with a flapping degree-of-freedom. The main rotor model used for the rotormap generation is presented in detail in ref. [3]. The rotor can be characterised completely by the six-state vector as a function of six performance parameters ($\vartheta_{3/4R}$, A_{1S}, B_{1S}, μ_X, μ_Y, and λ_S). To simplify the rotormap table-look-up, the six performance parameters are reduced to three using two successive transformations. First, the two in-plane velocity components (μ_X, μ_Y) are reduced to one, by aligning the rotor with the incident velocity vector. Second, the cyclic pitch angles (A_{1S}, B_{1S}) are eliminated, by referencing the rotor state in the control plane using the aerodynamic equivalence of feathering and flapping. The rotormap database thus consists of the six-state vector C_H/σ, C_Y/σ, C_T/σ, C_Q/σ, a_{1C}, and b_{1C}, as a function of $\vartheta_{3/4R}$, μ_C, and λ_C.

The rotormap database is quasi-static and therefore provision must be made to simulate blade dynamics, dynamic inflow effects, and transients due to body angular rates. Based on the solution for a flapping blade, the contributions to cyclic flapping angles can be divided into three components: i) a steady state component which is a nonlinear function of $\vartheta_{3/4R}$, μ_C, and λ_C, ii) flapping due to cyclic inputs, and iii) flapping due to body angular rates and dynamic inflow effects. The first component is obtained from the rotormap data tables. The second and third, treated as flapping increments to the steady state component, are obtained from closed form linear solutions of the flapping equations for the cyclic modes. The quasi-static cyclic flapping angles thus obtained are passed through a first-order filter to simulate the flapping dynamics. The time constant for the first-order filter is determined based on the solution for the regressive flapping mode, $\tau_\beta = 16/\gamma B^4\Omega_R$. The effects of transients due to body rates on the rotor state are obtained from closed form linear solutions and are added to the steady state values. Details of the rotormap approach and its implementation are presented in ref. [3].

The major advantage of the rotormap approach is its computational efficiency. The rotormap model can be executed in real-time using existing low-power computers for piloted simulation.

2.2.3 Blade Element Rotor Model

The rotormap main rotor model, while computationally very efficient, has several shortcomings. It is limited to only moderate variations of rotor RPM and temperature at which the rotormap was generated. A rotormap generated at 100% rotor RPM is used for most applications, it is restricted to maneuvers which involve a maximum of ±5% excursions in the rotor RPM. Large changes in temperature need different rotormaps to correctly account for stall and Mach number effects on the rotor blade. The transient solutions in the rotormap model, which are computed from closed form linear solutions and superimposed on the quasi-static solution, are valid only for maneuvers involving nominal body angular rates and for flight conditions where the blade section aerodynamics are in the linear range. Maneuvers involving high angular rates, roll-reversal for example, require a comprehensive blade element rotor model to account for the transient effects and to represent the non-linear blade aerodynamics. A blade element rotor model also provides the means to include aerodynamic refinements such as dynamic inflow, dynamic stall, radial drag, tip Mach-relief effects, and wake effects. It provides the necessary rotor degrees-of-freedom to dynamically couple the main rotor with the body and drive train. It can also more accurately predict blade loads and control loads. A blade element rotor model provides an overall comprehensive rotor modeling capability.

Furthermore, the advancements in low cost microprocessor based computers have made the real-time application of blade element rotor based flight models possible. A blade element rotor model was therefore added to FLYRT to also take advantage of the advances being made in computer hardware.

The blade element rotor in FLYRT is an extension of the steady state model which has been modified to include the transient solutions. The equations of motion for the blade are derived using the Lagragian approach. The blade displacements are represented by normal modes, to model different rotor types of retention systems. The generalised form of the equations of motion of the blade is represented as:

$$\ddot{q} + 2\varsigma\omega\dot{q} + \omega^2 q = Q_q/M_{qq}$$

where q is the generalised coordinate, ω is the modal frequency, M_{qq} is the generalised mass, and Q_q is the modal excitation force. In the lead-lag mode, ς can be used to represent the lead-lag damping coefficient. Detailed derivations of the blade element model development are presented in refs. [3 and 4].

The blade element rotor has provisions for blade flap, lead-lag, and torsional degrees-of-freedom. It has the rotor rotational degree-of-freedom and N-number of blades to interface with the body degrees-of-freedom. A single degree-of-freedom flexible drive train model, described in the next sub-section, is used to dynamically couple the rotor and body degrees-of-freedom.

The computational change required to make the steady state model conform with the flight model involved a "fly-to-trim" procedure which ensures smooth transition from a "trim" mode to a "fly" mode. In this approach, the basic blade asimuth interval depends on the prime time frame ($\Delta\psi = \Omega_R \Delta T$). Blade motion is computed at a sub-time frame using multi-rate sampling technique, as illustrated in figure 3. During trim, the rotor is first allowed to rotate for two to three revolutions to achieve an equilibrium position. For subsequent control perturbations, each rotor blade is allowed to sweep through nearly a quarter of a revolution and the blade motions are computed at each multi-sampling rate. In the "fly" mode, multi-rate sampling for blade motion is continued and the rotor forces and moments are averaged over the multi-rate sampling intervals for each prime-rate frame time. A multi-rate blade asimuth step size of around ten degrees was found to be adequate for most applications.

2.2.4 Main Rotor/Body/Drive Train Coupling

An important application of a rotorcraft flight simulation model is engine/airframe integration, where the engine fuel control system is designed to meet both engine performance and aircraft handling qualities requirements. Correct representation of the main rotor/body/drive train dynamic coupling in the flight model is essential to provide simulation support for engine/airframe integration.

The primary degrees-of-freedom involved in the rotor/body/drive train dynamic coupling are the main rotor lead-lag collective mode (η) and the rotor rotation (Ω_R), the body roll and yaw (p_B, r_B), and the drive train rotation (Ω_{DT}). In the rotormap model the lead-lag degree of freedom is not available; however, a rotor degree-of-freedom equivalent to the collective lead-lag mode is superimposed to excite the drive train dynamic model. In this approach, inertias of the engine and tail rotor branches, illustrated in figure 4, are combined with the main gear box as a single equivalent inertia in a gearless system. The stiffness and damping of this equivalent two degree-of-freedom system (Ω_R, Ω_{DT}) are tuned to obtain the characteristic drive train frequency of 2.7 to 2.8 Hz.

The blade element rotor model with N-blades provides the lead-lag degree-of-freedom required to excite the drive train dynamics. The main rotor/body/drive train coupled equations of motion are solved simultaneously, as presented in detail in ref. [4].

2.2.5 Inflow Model

The inflow model used in FLYRT for all three main rotor models is identical. A detailed development of the inflow model in FLYRT is presented in Appendix G of ref. [3]. The main rotor inflow model is based on momentum theory with a Glauert first harmonic distribution represented asimuthally as

$$w_i(x, \psi_R) = w_{i0}[1 + x\, f(\chi) \cos \psi_R]$$

where χ is the wake skew angle, $f(\chi)$ is the skewed wake profile, and w_{i0} is the mean induced velocity.

There are several ways of defining the wake skew profile $f(\chi)$, refs. [5 and 6]. The actual shape of $f(\chi)$ is critical only in the low speed, since the downwash has a hyperbolic characteristic approaching a zero value at high speed. The skewed wake profile $f(\chi)$ used in FLYRT is based on the vortex ring arrays of Castles and Deleeuw, ref. [6], where the normal downwash distribution is computed numerically as a function of wake skew angle. The values of $f(\chi)$ were extracted graphically from ref. [6]. Variation of induced velocity ratios as a function χ, for points on the longitudinal axes of the tip-path plane, were used. This skewed wake profile can be tuned by correlation with flight test data.

The skewed wake profile has a strong effect in the low speed transition flights. For steady state trimmed flights, the skewed wake profile in the low speed range ($30° \leq \chi \leq 60°$) can be tuned based on low speed flight test data covering level flight forward, backward, left and right. The skewed wake profile can be further tuned for dynamic flight conditions, if time histories of suitable maneuvers are available. The applicable maneuver is a pedal turn in hover with wind up to 10 knots. In this maneuver, as the incident velocity vector rotates relative to the aircraft, phased roll and pitch moments are induced by the skewed wake to which the aircraft responds. Such tuning typically result in substantial change in the skewed wake profile for the low speed range compared to those of refs. [5 and 6].

The global inflow model presented by Gaonkar and Peters in ref. [7] is based on the actuator disc theory

in which the mean and first harmonic downwash components are formulated as functions of the main rotor thrust, and aerodynamic hub pitching and rolling moments. This model is highly suitable for a blade element main rotor model and is being considered for implementation in FLYRT.

The discussion of the inflow model up to this point has been quasi-static. In practice, it takes a finite time for the influence of the impulse across the actuator disc to propagate, an effect which can be interpreted as the apparent mass of an indeterminate body of air. A simple concept is to assume that a cylindrical volume upstream and downstream of the actuator disc is affected. The dynamics of the axial inflow and angular inflow are derived considering the thrust and moment developed by an actuator disc.

The time constants associated with the dynamic inflow parameters are well established in the literature, both from tests and theoretical predictions, refs. [8 and 9]. In FLYRT, the time constants for both the mean and first harmonic components are treated as tuning parameters. Their values are determined based on validation against flight test or pilot's opinion in a manned simulator.

Ground effects are included in the inflow based on the Cheeseman and Bennett model, ref. [10]. The ground effects model in FLYRT enables ground mode operations, landings, and take-offs in manned simulators.

2.3 Fuselage Model

The fuselage has provision to model individual components such as the bare fuselage, wings, and store combinations for any given configuration, whenever the pertinent wind tunnel data are available. The aerodynamic data are presented in the body axes system and in coefficient form (e.g. F_{orce}/q, ft^2; M_{oment}/q, ft^3). Wind tunnel test results are used for low angles-of-attack and sideslip angles, α and β of $\pm 20°$. For high angles of α and β, the fuselage longitudinal and lateral forces and moments are represented based on the equations presented in ref. [11]. A phasing scheme is adapted to transition from low angles to high angles. Typical fuselage aerodynamic data for the lift, drag, side force, roll, pitch, and yaw moments, presented in figure 5, cover ± 180 degrees of α and β. For entry into the aerodynamic data functions, the angle of attack and sideslip are derived from the body axes components of velocity. These velocity components include additions for rotor downwash effects.

The effects of rotor wash on the airframe is included in the model. The technique used provides the essential effects of increased interference velocity with increased rotor load and decreased interference as the rotor wake deflects rearward with increased forward speed.

2.4 Horizontal Tail Model

The horizontal tail is treated as an aerodynamic lifting surface with lift and drag coefficients computed as functions of angle-of-attack. Mutual interference with the anti-torque system is neglected, since typically the aerodynamic database available is generated by a powered model composed of a tail-off fuselage and main rotor. The parameters extracted from the database are a fuselage blockage factor and an effective main rotor induced flow field resolved along the longitudinal and vertical axes. This flow field is normalised by the main rotor mean momentum downwash.

The rotor downwash at the empennage, which depends on rotor loading and rotor wake skew angle, is derived in a similar manner to the downwash at the fuselage. To account for the main rotor wake asymmetry, the horizontal tail surface is divided into two panels for computing the interference effects. A provision is made for dynamic pressure ratio correction to be applied to the empennage components.

2.5 Anti-Torque Models

The anti-torque module has two options to model different MDHC helicopters:

1. Conventional Tail Rotor/Vertical Tail System.
2. Advanced Anti-Torque System.

2.5.1 Conventional Tail Rotor/Vertical Tail System

The McDonnell Douglas Helicopter Company's AH-64A Apache and MD500 helicopters have the conventional anti-torque system which consists of a tail rotor and vertical tail. The strong mutual aerodynamic interference between the tail rotor and vertical tail, because of their close proximity to each other, is modeled in an iterative loop. The interference model is formulated to cover the low speed and high speed flight regimes with a gradual transition between them, as illustrated in figure 6. At low speeds, the tail rotor sees the vertical surface as a ground plate, and thus generates more thrust than an isolated rotor. In compensation, this excess thrust is countered by tail rotor wake induced flat plate drag. Significant parameters in the mutual interference model are the lateral separation normalised by the tail rotor radius, the ratio of area influenced by the ground plate to total disc area, and the ratio of area wetted by tail rotor wake to total effective vertical tail area. At high speed, the two components are treated as a Prandtl biplane, with span loading as the significant additional parameter. The boundaries of the transition band are determined as a function of tail rotor wake skew angle influenced by the main rotor wake. Mutual interference is computed as increments to angle-of-attack of the vertical tail and the tail rotor actuator disc plane.

The vertical tail is treated as an aerodynamic lifting surface similar to the horizontal tail. The tail rotor is modeled analytically (linear closed form) using strip/momentum theory. A uniformly distributed inflow is assumed. A teetering rotor model with pitch/flap coupling is used for most applications.

2.5.2 Advanced Anti-Torque System

The advanced anti-torque/directional control system, which is unique to McDonnell Douglas Helicopter Company's MD520N/MD530N and MDX models, dispenses with the tail rotor. The model has three basic sources of torque reaction: circulation control tail boom, thruster, and vertical stabiliser. Torque reaction is shared by the three sources according to the flight condition. Schedules for the vertical stabiliser incidence, thruster opening, fan pitch, and opening and closing of the slots in the boom are based on airspeed, collective stick, and pedal position. A FLYRT implementation of the advanced anti-torque system is illustrated in figure 7.

The internal performance of the advanced anti-torque system is based on a fanmap provided by the fan manufacturer. The map relates the fan states including total pressure ratio, mass flow rate, and blade pitch for specific ambient conditions. This information is used to generate tables for total pressure ratio and volumetric flow rate based on fan pitch and discharge area which includes the slot and thruster areas. Discharge velocities are calculated assuming that the mass flow expands isentropically to ambient pressure.

Performance of the circulation control boom is based on wind tunnel test data coefficients of lift and drag of the boom and are tabulated as functions of slot momentum coefficient and main rotor wake incidence angle at the boom.

2.6 Landing Gear Model

The AH-64A Apache landing gear is modeled in FLYRT. The model has three independent landing gear units interfacing with a rigid airframe. Each sub-model represents the dynamic characteristics of the appropriate landing gear unit. Since these models are elaborate, a table-look-up procedure to use the database has been followed, similar to that described for the rotormap main rotor. Two off-line codes, one each for the main gear and tail gear models, are used to generate the databases which contain reaction force as a function of velocity and displacement, all resolved along the airframe vertical-axis. The landing gear model provides logic for detecting ground contact as determined by the overall ground clearance and attitude within an Earth oriented frame of reference. It is interfaced with the flight controls module for ground mode logic. A terrain model suitable for simulating landing, take-off, and taxiing is provided, and features a ground plane slope of up to 10 degrees.

2.7 Engine Models

Engine models in FLYRT are aircraft specific and are adapted from the code, data, and flow charts provided by the engine manufactures. Engines for the McDonnell Douglas Helicopter Company's production helicopters modeled in FLYRT are:

1. T700-GE-701 Engine for the AH-64A Apache.
2. Allison C20R Engine for the MD500 Series.

2.7.1 T700-GE701 Engine Model

The T700-GE-701 engine consists of a five-stage axial and a single stage centrifugal compressor, an annular combustion chamber, a two-stage axial flow gas generator turbine, and a two-stage independent power turbine, ref. [12]. The first two stages of the compressor are variable geometry inlet guide vanes and stator vanes which are controlled as a function of inlet temperature and gas generator speed. The power turbine has a coaxial shaft which is connected to the output shaft assembly at the nose of engine. The power turbine is treated dynamically as an integral part of the drive train and its performance is dependent on the instantaneous gas generator speed and compressor discharge pressure.

The T700 fuel control system provides power modulation for rotor speed control, over speed protection, torque matching for multiple engine installations, and over temperature protection, ref. [13]. Control of the gas generator is governed through the interaction of the hydro-mechanical unit (HMU) and electronic control unit (ECU). The HMU meters the required fuel to the engine for gas generator speed control as constrained by an acceleration/deceleration schedule. The acceleration/deceleration schedules protect against engine stall and flameout, respectively. Inputs to the HMU are the power available spindle angle (PASA), load demand spindle angle (LDSA), and a trimming signal from the ECU. The PASA is mechanically linked to the power lever which has three positions, "off", "ground Idle", and "fly". The governor reference, which is set by the PASA, is modified mechanically by the collective pitch position through the load demand spindle. This signal provides load anticipation for immediate and accurate gas generator response.

The ECU trims the engine system to maintain rotor speed and limit power turbine inlet temperature while satisfying the load requirements. Functioning as the power turbine governor, the ECU selects the maximum of two signals, the first based on the speed error, the second on a margin of turbine inlet over a maximum allowable reference temperature. The resulting signal is processed to generate a proportional-cum-integral isochronous command before merging with the transient droop improvement (TDI) signal dependent on the collective pitch lever position. The TDI provides load anticipation to supplement a mechanical signal transmitted to the HMU by direct linkage between the collective pitch lever and the load demand spindle. The output of the ECU is a commanded fuel flow supplied to the HMU.

Initialisation of the engine/ECU is performed through the model from known steady state inputs and outputs. All intermediate states within the model are set based on the steady state power turbine speed error (zero), temperature margin, and commanded fuel flow.

The T700 engine code in FLYRT has a twin engine model which enables simulation of one engine inoperative (OEI) conditions and engine mismatch conditions.

2.7.2 Allison C20R Engine Model

The Allison C20R turbine engine and control system model is based on the block diagrams and data provided by the manufacturer. It is suitable for simulating the transient behavior of the engine. The Allison C20R engine model, when compared to the T700 engine model, is similar but considerably less complex. In addition to the power lever position and collective pitch position as pilot inputs, a beeper switch is available for the pilot to trim the engine response. The C20R model has three major components: i) power turbine governor, ii) fuel control, and iii) engine model. The modeling approach to compute engine response is based on data tables. The C20R engine model has been used successfully to study the drive train torsional response on the MD500 helicopter.

2.8 Flight Control System Model

The AH-64A Apache flight control system, which is modeled in FLYRT, consists of mechanical and electrical links from the pilot and copilot/gunner (CPG) stations to the collective, longitudinal cyclic, lateral cyclic, and tail rotor actuators. Each actuator hydraulically sums the pilot/CPG mechanical inputs with those from the electrical link via electrohydraulic servo valves. In the lateral, longitudinal, and directional axes, the electrical links provide limited authority stability and command augmentation (SCAS) functions for a variety of manually and/or automatically selectable modes. The authority limits are ±10% of full control authority in the lateral and directional axes, and 20% forward and 10% aft in the longitudinal axis. In the event of a mechanical link failure such as a jam or severance, the electrical link control path provides a full authority backup control system (BUCS) in all four control axes. The SCAS and BUCS control modes along with their associated monitoring and control logic are implemented in the digital automatic stabilization equipment (DASE/BUCS) sub-system. Detailed description of the Apache flight control system can be found in refs. [2 and 14].

The FLYRT flight control system model represents the Apache DASE/BUCS and the horizontal stabilator schedule. The DASE provides stability augmentation (SAS), command augmentation (CAS), hover augmentation (HAS), heading hold, attitude hold, and turn coordination. The horizontal stabilator schedule provides for desired aircraft pitch attitude.

The DASE functions in pitch, roll, and yaw axes are activated through three individual switches in the automatic stabilization equipment (ASE) panel in the aircraft. The attitude/hover hold functions are engageable through a separate dual function switch.

The SAS mode provides rate damping in pitch, roll, and yaw axes. When the yaw SAS is engaged, a limited authority turn coordination is provided automatically above 60 knots. The CAS, which augments the pilot control inputs, is an automatic function of the DASE whenever the pitch and roll SAS, and yaw SAS below 60 knots, are selected. The automatic disengagement of the yaw CAS function in ground operation is modeled by interfacing the landing gear model ground contact logic with the DASE model.

The HAS mode is engageable below 15 knots ground speed and 50 KTAS through the attitude/hover hold switch in the ASE panel, whenever the DASE pitch and roll modes are engaged. Heading hold function is also provided whenever the DASE yaw mode is engaged. The attitude hold function, engageable through the same HAS switch in the ASE panel, is provided above 60 KTAS with the pitch and roll modes engaged.

The force trim switch on the cyclic stick is modeled to interface with the McFadden control loader system in the manned simulator. This switch has three positions: force trim-on, force trim-off, and force trim release. The force trim-on position provides trim feel to the controls in the pitch, roll, and yaw axes. The force trim release allows for momentary release of the trim feel system and is used for retrimming the aircraft. The force trim-off position disengages the trim entirely. These three switches are modeled through two software flags.

The DASE engagement cockpit hardware switches in the ASE panel in the aircraft (yaw, roll, pitch, and hover augmentation/attitude hold) are modeled in FLYRT through software switches for nonreal-time applications, and cockpit interfaces are also provided for manned simulation.

The horizontal stabilator model for the AH-64A Apache has variable incidence with three modes of operation: i) fully automatic mode, ii) Nap-of-the-Earth/approach mode, and iii) manual mode. In the fully automatic mode, the stabilator is driven by a schedule based on indicated airspeed and main rotor collective pitch setting. In transient flights, a pitch rate law becomes active. The stabilator incidence in the automatic mode ranges from −5° to 25°. In the NOE/approach mode, operational below 80 knots, the stabilator incidence is set to 25°, trailing edge down. In the manual mode, which can be selected below 80 knots and is also available in the case of fully automatic mode failure, the stabilator incidence ranges from −9° to 35°. The stabilator acts more as a trim device because of the slow actuator rate.

The NOE/approach mode is activated through a switch in the ASE panel in the cockpit. The manual mode is activated through a switch on the collective stick. For the FLYRT Apache stabilator model, the necessary interface with cockpit hardware switches are provided for manned simulation.

In FLYRT, all the flight control system transfer functions are digitized using a zero-order hold reconstruction which is compatible with the Euler and trapezoidal time integration. The inputs to the flight control system module are: p, q, r, $\dot{\vartheta}$, A_{1S}, B_{1S}, $\vartheta_{T/R}$, ϕ, θ, ψ, u, v, w, β, and V_A. The outputs are limited authority control inputs in the pitch, roll, and yaw axes, and incremental angle of incidence for the horizontal stabilator. The sensors and actuator dynamics are not modeled.

3. FLIGHT MODEL VALIDATION AGAINST FLIGHT TEST DATABASE

The FLYRT flight simulation code has been extensively validated primarily against the AH-64A Apache flight test database, refs. [15 and 16]. Steady state trim correlations, and time domain and frequency domain validations have been performed, both to validate and to refine the flight model.

Steady state trim correlations at different speeds and directions of flight facilitate validation of several aspects of the model. Hover correlation enables refinement of the main rotor and tail rotor mean momentum downwash models. In addition, the tail rotor inflow in the presence of a vertical tail acting as a ground plate is refined. At low speed level flight (forward, rearward, sideward left or right) up to 40 knots, the main rotor first harmonic components of the momentum downwash and the effects of the main rotor downwash on the airframe components (fuselage, tail rotor/vertical tail, and horizontal tail) are validated. Also, the sideward flights exercise the high angle fuselage equations through the large sideslip angles encountered. At moderate speeds, around 80 knots, the main rotor downwash effects at high wake skew angles and the stabilator speed/collective schedule are validated. The high speed correlations enable accurate modeling of the effects of high advance ratio in the main rotor (high Mach numbers on the advancing side and high angles of attack on the retreating side), the effects of the vertical tail and tail rotor acting as a bi-plane, and the total drag of the airframe. The vertical descending flight cases checkout the provision for vortex ring state in the main rotor. The climbing and turning flight correlations validate the cross-coupling terms in the main and tail rotors and also the airframe.

Time domain dynamic response correlations are performed for simple step/doublet control inputs in individual axes as well as specific maneuver flights. Correlations for single axes control inputs are performed typically at three different speeds (hover, 80 and 130 knots) and in the four axes, yaw, roll, pitch, and vertical, in that order, to validate various transient computations of the model. Correlation of a yaw maneuver in hover establishes the accuracy of the tail rotor model. Through correlation of roll and pitch responses in hover, the skewed wake profile and the time constants of the first harmonic component of the dynamic inflow are tuned. Correlation of vertical axis response in hover validates the transient thrust computations and the time constant in the mean momentum downwash of the main rotor. At high speeds, correlation of yaw maneuvers identifies upgrades to the vertical tail and the interference factors. Comparison of responses in roll and pitch are used to refine the airframe modeling. In particular, the pitch axis correlation enables correct modeling of the pitch stability through the main rotor downwash interference effects on the horizontal stabilator. Specific maneuvers, such as one engine inoperative fly-away from hover, validate the engine/airframe/rotor interfaces of the flight model.

Frequency domain methods enable validation of the flight model over the entire frequency range of interest. Based on the frequency at which discrepancies occur, components and their model upgrades can be identified. Furthermore, frequency domain validation is required to meet the new ADS-33C, ref. [17], requirements for military rotorcraft.

3.1 Steady State Trim Validation

A brief description of the FLYRT trim procedure was presented in section 2, illustrated in figure 1. The parameters typically chosen for static trim validation against flight test are main rotor collective, longitudinal and lateral cyclic (δ_o, δ_s, δ_c), pedal position (δ_p), stabilator incidence (i_{HS}), total shaft horsepower (HP), and aircraft pitch and roll attitudes (θ, ϕ).

The pilot controls for validation results presented in this paper are provided in % of control actuator motion, inches of stick/pedal travel, or blade angles in degrees. Conversion between the three different units of control measurements, for the AH-64A Apache helicopter, are given below:

AH-64A Apache Control Rigging

Axis Stick/ Pedal	Actuator Travel	Blade Angle Deg.	Stick/ Pedal Inches	Stick/ Pedal Direction
Coll.	0%	0.0	0.0	down
Stick	100%	18.0	12.0	up
Long.	0%	20.0	0.0	forward
Stick	100%	-10.0	10.0	aft
Lat.	0%	-10.5	0.0	left
Stick	100%	7.0	9.0	right
Yaw	0%	27.5	0.0	left
Pedal	100%	-13.5	6.5	right

Figure 8 presents static trim correlation against AH-64A Apache flight test for steady level flights in forward, rearward, and sideward left and right directions. The rotormap main rotor in FLYRT was used to generate these results. The control positions predicted by FLYRT for the collective and lateral sticks are less than those of flight test; however, the correlations are better for the longitudinal stick and pedal positions. The total shaft horsepower, and roll and pitch atti-

tudes predicted by FLYRT show generally good agreement with flight test.

Figures 9 shows autorotation trim correlation, FLYRT (rotormap) against AH-64A Apache flight test. The collective stick positions are over predicted in the low speeds and under predicted in the high speeds. The rate of descent and pitch attitude show acceptable agreement with flight test. Pedal and longitudinal stick positions show good agreement. However, the lateral stick positions are over predicted for the entire speed range, which is opposite to the trend seen for the steady state trims shown in figure 8.

Results from the blade element rotor model for the static trim are not presented here. They can be expected to be nearly the same as the rotormap main rotor model. In steady state, the rotormap tables represent all the characteristics of a blade element rotor model, since the off-line code used for generating the rotormap is a blade element rotor model.

3.2 Time Domain Dynamic Validation

Dynamic response time histories are generated by executing the "fly" sequence in FLYRT, illustrated in figure 2. Two different methods are used to duplicate flight test maneuvers: i) FLYRT driven by flight test control time histories, and ii) maneuvers flown by a paper pilot. In method i), the simulation model is driven with measured control time histories. The flight model is trimmed as close as possible to the flight test condition. It is then driven by adding the trimmed controls to the perturbation controls which are obtained by subtracting the initial control positions from the measured data. This method eliminates propagation of any intial condition errors in the dynamic response. In method ii), the maneuvers flown in flight test are duplicated in conjunction with the paper pilot software in FLYRT. The paper pilot combines the control inputs with an adaptive control system to duplicate the pilot action in executing a desired maneuver.

The FLYRT (rotormap) dynamic validation against the Apache flight test data performed in recent years is documented in ref. [15]. A dynamic validation criteria provided by NASA was used as a guideline to show correlation against flight test. These dynamic validation criteria are considered appropriate for validating the dynamic response of a flight model. The criteria used are:

1. *Short-term on-axis responses: The peak value and 50% rise-time of the simulation and flight values shall match to within 20% of the flight values.*
2. *Long-term on-axis responses: The stability trends (i.e. converging or diverging) shall be consistent with the flight data.*
3. *Off-axis responses: The trend of the off-axis responses shall have the correct signs (i.e. increasing positively or negatively) following the on-axis input during the time period up to the 100% rise-time. This requirement shall be discarded for individual off-axis responses if, during the time period up to the 100% rise-time, that specific off-axis response deviation has a peak flight value less than 20% of the on-axis peak flight response for the same input.*

For the cyclic stick and pedals, the "on-axis responses" are defined as: the pitch rate (q_B - deg/sec) response to longitudinal cyclic, the roll rate (p_B - deg/sec) response to lateral cyclic, and the yaw rate (r_B - deg/sec) response to pedals. For the collective, the "on-axis response" is the vertical acceleration (a_z - g's). The "off-axis response variables" are the remaining three response variables respectively for each axis.

The simulation results presented in ref. [15] were generated using the measured control inputs to drive FLYRT, described previously as method (i). Representative validation results from ref. [15] for the directional, lateral, longitudinal, and collective axes, are presented in figures 10 through 13. Only the primary axis (on-axis) responses are shown.

The FLYRT response at hover to a half-inch left directional doublet is shown in figure 10. In the original model (version 5.0), the peak yaw rate is considered marginally acceptable. The discrepancy was traced to control rigging calibration data which was subsequently upgraded (version 5.1) based on rigging data measured from four different production aircraft. Differences between upgraded control rigging and the original control calibrations were minimal everywhere except at full right tail rotor blade angle which was 25% less. Updates to control calibrations resulted in excellent correlation in yaw rate rise time and peak value. Both on-axis (primary axis) and off-axes (secondary axes - not presented here) responses were considered acceptable.

Figure 11 shows the predicted response to a half-inch right lateral doublet at 80 knots. Peak roll rate is acceptable but the 50% rise time does not match. The increasing roll rate at six seconds in the flight test data appears to be independent of control inputs and could be related to external disturbances. The off-axis responses predicted for this case (not presented here) were found acceptable, except for the normal acceleration.

In figure 12 the longitudinal response correlation at 130 knots is presented. The updated FLYRT version 5.1 shows significant improvements over version 5.0. The pitch response obtained from version 5.1 to a half-inch aft doublet agrees well with flight test data. The difference between versions 5.0 and 5.1 is a modification to the main rotor downwash effects on the horizontal stabilator. Interference factors involving the magnitude and direction of the wake hitting the stabilator were tuned to correlate with flight test pitch rates. The off-axis response, except in the roll axis,

were acceptable. The roll rates predicted showed opposite trends. Again, the off-axes results are not presented here.

Figure 13 shows the FLYRT response to a half-inch up collective doublet at 130 knots. The normal acceleration peak does not exactly match the measured peak but shows the correct trend. The off-axis responses for this case, not presented here, met the acceptability criteria.

In summary, based on the dynamic validation criteria employed, the overall FLYRT simulation is considered acceptable for the short-term response. In off-axes, certain coupling effects showed opposite trends leading to error buildup in the long-term comparisons. It must be pointed out that, in most cases, the magnitude of the off-axis responses are much less compared to the on-axis response. Significant improvements in the FLYRT predicted responses can be expected with the blade element rotor model.

In addition to the time history correlations documented in ref. [15], several other similar correlations of FLYRT against AH-64A Apache flight test database have been performed. As an example, the AH-64A Apache one engine inoperative (OEI) fly-away from hover maneuver is presented in figure 14. The specification for multi-engine rotorcraft require that the allowable altitude loss following a single engine failure shall be no more than 50 feet (15M). The validation criteria used for figure 14 was to match the simulation predictions to the flight test time histories as close as possible, which is more demanding than the NASA validation criteria used for results shown in figures 10 through 13. The control positions, engine torques, normal acceleration, and radar altitude from FLYRT simulation show good agreement with flight test. However, the main rotor speed predicted by FLYRT for this maneuver shows poor correlation.

The OEI fly-away from hover maneuver was created using a maneuver routine and the paper pilot software, described previously as method (ii). Several other flight test maneuvers using this method have been simulated in FLYRT. Of the maneuvers simulated, some were performed for the purpose of validating against flight test data, and others as part of simulation applications for design and development, which are presented in a latter section.

3.3 Frequency Domain Validation

Frequency domain validation of FLYRT (rotormap) was initially performed in the context of manned simulation, ref. [18], to improve pilot acceptance of the simulation environment. The ADS-33C, ref. [17], handling qualities specification for military helicopters for small amplitude attitude change maneuvers is defined primarily in the frequency domain in terms of bandwidth and phase delay. The criteria relate the aircraft frequency response to pilot ratings for different piloting tasks. The pilot ratings obtained from a manned simulation are used to identify simulation fidelity issues through the frequency response analysis of the simulation environment. In addition, the frequency response comparisons also identify flight model components for fidelity improvements, based on the frequency content.

Frequency response analysis was performed by flying frequency sweep maneuvers in the batch (nonreal-time) FLYRT and superimposing the effects of the manned simulation environment, such as the control loader and visual image generator, as pure time delays. Frequency sweep techniques recommended in refs. [19 and 20] were used to generate time history responses which are then used for frequency domain analysis.

The FLYRT predicted frequency responses against the AH-64A Apache flight test data for pitch rate to longitudinal cyclic and roll rate to lateral cyclic are compared in figures 15a and 15b, respectively. The responses are presented in terms of magnitude and phase, for 130 knots and DASE-off condition.

In figure 15a, coherence values of near 1.0 for frequencies above 0.5 rad/sec show that there is good identification of the responses above this frequency. The magnitude response of the model is about 4 dB greater than the aircraft for frequencies above 2 rad/sec. This trend is consistent with those seen in the time domain validations which show larger pitch response to higher frequency longitudinal cyclic inputs.

In figures 15b, low coherence for the flight test data indicates either the influence of off-axis controls or that flight test data on the rate response should be suspect. The recommended (ref. 20) usable frequency range is where the coherence is greater than 0.8 for the identified response. Roll responses shows poor coherence for the low frequency range; thus, the comparisons are limited to the higher frequencies wherever possible. The high frequency roll rate response is considered acceptable. The yaw rate response comparison, not presented here, showed poor coherence and hence the validation was inconclusive.

The magnitude and phase delay data for the pitch, roll, and yaw axes were transformed to the ADS-33C short term attitude response requirements. For the 130 knots, DASE-off condition, the pilot rating levels obtained from FLYRT were in good agreement with those obtained from the AH-64A Apache flight test data. The pilot rating levels are not presented here, they can be found in ref. [18].

In summary, the magnitude and phase frequency response comparisons between FLYRT and flight test confirm results found in several time domain validation efforts. In general, the FLYRT model responds more strongly to pitch control inputs at higher frequencies. These results indicate that the main rotor flapping dynamics and rotor/body coupling procedure used in the rotormap main rotor model need to be up-

graded. Similar frequency domain validation for the blade element main rotor model, because it will eliminate shortcomings of the rotormap model, can be expected to provide better correlations against the flight test database.

4. APPLICATIONS OF FLIGHT SIMULATION FOR ROTORCRAFT DESIGN AND DEVELOPMENT

The FLYRT flight simulation model applications presented here are: the simulation of a power-off emergency landing procedure for a OH-6A Cayuse helicopter, the AH-64A Apache empennage redesign, piloting techniques for terrain avoidance maneuver, safety of flight for air-to-air combat flight envelope expansion, advanced flight control law development, and flight test support for engine/airframe integration for the AH-64A Apache upgrades. For these applications, the simulation objective, specific model refinements required, and correlation against flight test whenever available, are presented. Applications of MDHC's flight model in manned simulators are also presented.

4.1 OH-6A Cayuse Helicopter Power-Off Emergency Landing

Simulation of power-off emergency landings is required to design the helicopter main rotor autorotative inertia for safe landing. During the early stages of FLYRT development, it was applied to simulate the power-off emergency landing procedure for a OH-6A Cayuse helicopter, presented in ref. [1]. The flight model in this application consisted of three longitudinal degrees of freedom, a rotormap representation for the main rotor, and a linear engine model driven by turbine speed error. A paper pilot based on adaptive control laws was used to execute the maneuver.

Figure 16 illustrates validation of the emergency landing, initiated from 50 knots, against the OH-6A Cayuse helicopter flight test data. The emergency landing was simulated by dividing the maneuver into four major segments, pilot's initial reaction, initial flare, final flare, and pre-touchdown. The initial reaction by the pilot, triggered by a rapid decay in the rotor speed following engine failure, is to push the stick forward. The second action, which lasts for the next 2.5 seconds, is the initial flare when the pilot pulls back the stick to command a nose-up attitude, and dumps collective to a minimum, to reduce both the helicopter's downward acceleration and the rotor deceleration. The third stage is the final flare, for the next 1.5 seconds, when the helicopter achieves a nose-up attitude for rapid deceleration. The rotor speed reaches maximum and is controlled by progressively increasing the collective pitch. The fourth stage is the pre-touch down, which starts about 5 seconds into the maneuver, when the rate of descent is controlled to be within the safe margin. Rapid application of the collective pitch reduces the residual rotor energy. Rate of descent, pitch rate, forward ground speed, and nose-up attitude are all controlled through longitudinal cyclic and collective for a safe landing.

The FLYRT predicted results correlated well with flight test data for this maneuver. The maneuver illustrated in figure 16 is routinely used in FLYRT to study the effects of change in rotor inertia on safe emergency landing requirements of a helicopter.

4.2 AH-64A Apache Empennage Redesign

One of the major applications of FLYRT during the AH-64A Apache full scale development was the empennage redesign to improve pilots visibility. A technical history of the Apache empennage redesign is presented in ref. [21]. The prototype configuration had a T-tail which caused a high nose-up pitch attitude during approach, in Nap-of-the-Earth (NOE) flights, and in climb, resulting in poor pilot visibility. The T-tail was changed to a low horizontal tail, and eventually to a stabilator, which resulted in a much reduced nose-up attitude and thus better visibility for the pilot. The AH-64A Apache production configuration is shown in figure 17a.

The horizontal stabilator control system for the AH-64A Apache is similar to that of the UH-60 Blackhawk helicopter. The horizontal stabilator has three modes of operation: i) automatic mode, ii) NOE/Approach mode, and iii) manual mode. In the automatic mode, the schedule is a function of the collective position, indicated longitudinal airspeed, and pitch rate. FLYRT simulation was used in establishing the values of control system gains in the speed and collective paths in the automatic mode, to achieve the desired aircraft pitch attitude and longitudinal stick travel. Limit on the maximum stabilator incidence, 35 degrees trailing edge down in the manual mode, was also set. In addition, a parametric study of the horizontal stabilator wetted area required was also performed using FLYRT.

Two aspects of the horizontal stabilator model in FLYRT were upgraded during this simulation to improve aircraft longitudinal trim predictions. First, the main rotor wake interference effects on the horizontal stabilator were refined using data obtained from powered AH-64A Apache model wind tunnel tests. Second, the stabilator was divided into two independent surfaces, left and right, to account for the asymmetric flow effects of the main rotor advancing and retreating sides. The model upgrades were critical for computing correct aircraft pitch attitudes and longitudinal stick positions in low speed flights. Figure 17b shows the good correlation obtained for FLYRT predicted pitch attitudes and longitudinal stick positions against flight test data for low speed level flights, at a fixed stabilator incidence of 35 degrees.

Application of FLYRT for the successful redesign of the AH-64A Apache empennage, and subsequent confirmation of the simulation results during flight test,

established FLYRT as a valuable flight simulation tool at McDonnell Douglas Helicopter Company.

4.3 AH-64A Apache Terrain Avoidance

Military helicopter specifications for terrain avoidance maneuvers require that a helicopter should able to perform three-second sustained symmetrical pull-ups at 1.75g, initiated at an airspeed of 150 KTAS, not less than 120 KTAS at the end of the maneuver, and two-second sustained symmetrical push-overs at −0.5g initiated at an airspeed of 120 KTAS.

FLYRT was validated against the AH-64A Apache flight test data for the terrain avoidance maneuver, illustrated in figure 18, from ref. [22]. In order to simulate the maneuver using a paper pilot, the pilot action was divided into three stages, pull-up, push-overs, and recovery, which are clearly identifiable from the flight test data. The maneuver is executed using both the longitudinal stick and collective: the stick back for pull-up, followed by stick forward together with the collective down for push-over, and finally stick back for recovery. The lateral stick and pedal are used to hold the aircraft roll attitude and heading. The rotor speed is controlled through collective pitch.

FLYRT predicted results for the terrain avoidance maneuver, when compared against the AH-64A Apache flight test data, figure 18, show good correlation for the control positions as well as the aircraft states. The terrain avoidance maneuver feature in FLYRT is used to demonstrate the load factor capabilities of advanced rotor designs.

4.4 AH-64A Apache Air-to-Air Combat Flight Envelope Expansion

Air-to-air combat flights in helicopters, although not as common as in fixed wing fighters, involve aerobatic maneuvers which take the aircraft to the extremes of the flight envelope and some times beyond, ref. [23]. Aerobatic maneuver capability of a helicopter, in addition to air-to-air combat capability, serves two other purposes. The first obvious purpose is to perform spectacular maneuvers in demonstration flights and air shows. The second, which is more important for pilot and crew safety, is the helicopters' ability to regain normal flight in emergency situations. Emergency situations could arise from any number of reasons including abrupt evasive maneuvers, turbulent weather conditions, strong gusts, and disorientation of the pilot, all of which could result in unsafe aircraft attitudes. The aerobatic capabilities of the helicopter are highly useful to maneuver the aircraft into safety.

For the AH-64A Apache advanced attack helicopter, aerobatic maneuver simulations were performed using FLYRT before clearing the aircraft for air-to-air combat flight tests. The main objectives of the simulation were twofold: i) to predict the load factors at critical points in the maneuver for detailed stress analysis of primary airframe components and ii) to provide a series of decision points to the pilot to ensure safety of flight. The aerobatic maneuvers simulated include execution of a 360 degree vertical loop and 360 degree roll right and left. These maneuvers involve high speeds and high load factors and exercise the rotor to its limits.

The paper pilot in FLYRT was used to simulate the maneuver. The piloting technique to execute a vertical loop as illustrated in ref. [23] was used as a starting point. A detailed description of the AH-64A Apache air-to-air combat maneuver simulations is presented in ref. [24], the vertical loop maneuver from which is described here. Figure 19 shows the time history of aircraft speed and load factors for the vertical loop maneuver. The entry speed for the loop maneuver was identified to be between 120 to 140 knots. Speeds below 120 knots were insufficient to generate the looped flight path. Aircraft speeds above 140 knots exceeded the transmission torque limit over the high load factor regions of the maneuver, and also, unacceptable rotor stalls were detected.

The first major decision point in executing the maneuver is when the speed falls in the range 80 to 100 knots, from 140 knots, and the load factor increases to around 2.0g. From here, the longitudinal aft stick must be increased further to achieve a pitch rate of up to 50 deg/sec. This stick position is held until the next major decision point which occurs at the end of the inverted flight with the aircraft in a vertical nose down attitude. At this point, forward stick is progressively applied to attain a straight and level flight. During transition from vertical to level flight, collective pitch is increased to keep the rotor RPM to within ±5% to 10%. Lateral stick activity was not required; however, left pedal inputs were required for compensation at very low speeds.

4.5 Advanced Flight Controls Development

McDonnell Douglas Helicopter Company has designed and flight tested an experimental fly-by-wire control system on the AH-64A Apache, ref. [25]. During development of the fly-by-wire flight control system, FLYRT was used both in the nonreal-time mode and in the manned simulator.

Currently, the rotormap FLYRT is used to support control law development. However, the modern day high gain control laws require a blade element rotor model to provide sufficient bandwidth for the control system design. An aeroelastic blade element rotor with coupled flap, lead-lag, and torsion degrees-of-freedom dynamically coupled to an elastic airframe is required to develop the correct control system gains. Use of a comprehensive flight model to develop control laws will result in reduced development flight test cost.

4.6 AH-64A Airframe/Engine Integration

A blade element main rotor model is required not only for high gain fly-by-wire control law development, but also for several other applications. One such appli-

cation discussed here is Apache airframe/engine integration to obtain the desired aircraft handling qualities and engine response. Engine responses of interest include torque overshoot, rotor RPM droop, engine load sharing, and torque mismatch. A major model upgrade to FLYRT in the past two years has been the addition of a blade element rotor model, ref. [4], described in section 2. A blade element rotor model was required to accurately simulate the engine/drive train responses to validate the engine fuel control system for engine upgrades and modifications.

One of the critical maneuvers to be flight tested in order to validate the adequacy of the engine fuel control system is roll-reversal in high speed flight. This maneuver, initiated from a steady straight ana level flight, is executed using the lateral stick and maintaining heading. The collective stick remains fixed at its trimmed position. The maneuver is often referred to as an "uncompensated maneuver" since the engine control system has provision for feed forward compensation as a function of collective motion, to produce proper engine response, but the collective is not moved. The engine response is primarily driven by the turbine speed error during this maneuver. The maneuver results in high roll rates, in excess of 50 deg/sec. High roll rates coupled with the aircraft forward speed around 130 knots results in retreating blade stall. These effects produce a sharp increase in the rotor torque load, which generates a torque spike in the engine response. For helicopters with rotor rotation direction which puts the retreating blades on the left, a right-to-left rapid roll produces a more severe torque spike. A flight simulation model should be capable of predicting the torque spike, both in magnitude and phase, for proper engine fuel control system design.

FLYRT has been used to predict the characteristic torque spike in rapid roll maneuvers, presented in detail in ref. [4]. For the purpose of illustrating this application, the results and discussion for the right-to-left rapid roll from ref. [4] are presented here.

Figure 20a presents the comparison of FLYRT predicted results, both from the rotormap and blade element rotor models, against the AH-64A Apache flight test data. In this maneuver, initiated from a steady level flight, the aircraft is rolled 90 degrees to the left and immediately rolled back to wings level attitude, executed in about 4 to 5 seconds. The parameters compared are the roll attitude (ϕ), roll rate (p_s), torque for the No.2 engine (Q_{T2}), and the main rotor speed (Ω_R). Both ϕ and p_s from FLYRT simulations show good correlation against the flight test data. The main rotor RPM (Ω_R) droop from the blade element FLYRT compares better with flight test than that from the rotormap FLYRT. The engine torque (Q_{T2}) predicted by the blade element model is much closer in magnitude to the characteristic torque spike seen in the flight test data when compared to that predicted by the rotormap model. The magnitude of the engine torque predicted by the rotormap model is highly attenuated when compared to flight test; however, the onset of the event is predicted correctly.

Prediction of transient effects due to body angular rates in the rotormap FLYRT, described in section 2, is limited to nominal angular rates, since the transients are computed based on closed form linear solutions. Also, the rotormap main rortor model cannot account for stall at the blade element level because the rotor is treated as a disc for aerodynamic representations. However, the engine torque from the rotormap model in the linear aerodynamic range is in close agreement with that from the blade element model. The rotormap result has the correct phase, but is much attenuated in magnitude. This result shows that the rotormap model can be used for preliminary engine/airframe efforts. The blade element rotor model can subsequently be used to perform a final design of the engine fuel control system.

To obtain a better understanding of the rotor mechanism involved in generating the characteristic torque spike in the engine, an illustration of the blade element rotor response is presented in figure 20b. In this figure, rotor blade torque (Q_R), and blade section lift and drag coefficients (C_L, C_D) at a blade radius of 0.86R, as a function of rotor asimuth, are presented for the reference blade (#1). The blade #1 asimuth corresponds to a typical time slice during which the engine torque spike occurs. The C_L plot shows that the blade section reaches stall in the fourth quadrant, around a blade asimuth of 300 degrees. The C_D plot shows a corresponding drag rise. The sharp increase in rotor torque, (Q_R), occurs in response to the blade drag rise. The blade element rotor model represents, at the element level, the drag due to stall and the changing aerodynamic environment of different blades due to asimuth spacing. It is therefore better able to predict the torque spike magnitude as compared to the flight test data.

A blade element rotor model provides the capability to accurately model blade aerodynamics at the blade element level, which is required to predict the correct engine response. In addition, it provides the lead-lag degrees-of-freedom required to model the rotor/body/drive train dynamic coupling (described in section 2) in order to properly predict the drive train response, which is critical to a successful integration of engines with the airframe.

4.7 Manned Simulation Applications

Application of FLYRT for manned simulation covers a wide range of simulators. In 1981, FLYRT was used on the NASA/Ames FSAA (Flight Simulator for Advanced Aircraft) to simulate the OH-6A/NOTAR demonstrator for safety of flight before full scale modifications to the aircraft could begin. In 1983, MDHC teamed with Singer-Link to develop a FLYRT based

flight model for the U.S. Army's Combat Mission Simulator (CMS) for the AH-64A Apache. As part of the Advanced Rotorcraft Technology Integration (ARTI) program, which was the predecessor to the U.S. Army's LH program in 1984, a FLYRT model of the AH-64A Apache was implemented in the McAir (MDHC) simulator. A simplified version of FLYRT was generated for the U.S. Army's Cockpit/Weapons Emergency Procedure Trainer (CWEPT), in 1985. In the subsequent years, FLYRT has been implemented in the MDHC fixed base full mission simulators, where it is primarily utilised for engineering simulation of the AH-64A Apache and its variants. During 1989, a FLYRT model of the AH-64A Apache was implemented in the vertical motion simulator (VMS) at NASA/Ames for the U.S. Army. The main objective was to provide the Army with a capability to study potential accident scenarios, and for accident investigations. Pilot evaluations of the AH-64A Apache FLYRT in the MDHC full mission simulators and in the VMS at NASA/Ames, are presented next.

4.7.1 AH-64A Apache FLYRT on MDHC Simulators

The McDonnell Douglas Helicopter Company full mission simulators are currently fixed base, with an interchangeable cockpit enclosed in a 20 ft. diameter dome. A General Electric Compuscene IV image generating system is used for the visual simulation. Also available are Evans & Sutherland and Sogitec visual systems for specific applications. The image is projected on the dome through a servo-optical projection system (SOPS) with a head-tracker driven high resolution insert. The visual system used in the dome gives an excellent field-of-view for the pilot. At the present time, the rotormap FLYRT model is used for manned simulation.

In recent years, there has been increased emphasis at McDonnell Douglas Helicopter Company to improve the fidelity of the simulation environment, ref. [18]. Various aspects of the simulation environment were upgraded towards improving the simulation fidelity. The real-time flight model was updated to the most recent version of FLYRT. The McFadden control loader system force-feel characteristics were re-calibrated to match the aircraft measured characteristics. Texture patterns in the visual database were upgraded to improve visual cues for precision flying. Improvements to aural cues and force cues (g-seat) were also investigated.

In order to assess the improved fidelity of the simulation, ratings were obtained for a series of piloting tasks. The tasks chosen were similar to the ADS-33C, ref. [17], flight test maneuvers. It included hover turns, hovering lateral step, hovering bob-up, terrain flight, forward flight pop-up, approach/landing/take-off, high speed flight, NOE deceleration, and pinacle hover. All these piloting tasks were flown with the aircraft automatic flight control system (DASE) turned on. The overall pilot ratings (Modified Cooper-Harper Handling Qualities Ratings - HQR) obtained for the AH-64A Apache simulation from three different pilots were 4/4, 4/5, and 7.5/7.0 (adequacy/work load), details are presented in ref. [18]. These ratings indicate that for the majority of the pilots the AH-64A Apache simulation has a nearly level-1 (satisfactory without improvement) acceptance.

4.7.2 AH-64A Apache FLYRT on the VMS at NASA/Ames

The FLYRT model currently implemented on the NASA Ames VMS has a rotormap main rotor model. A blade element rotor model for the AH-64A Apache application on the VMS is under development by the U.S. Army Aeroflightdynamics Directorate.

A description of the NASA/Ames VMS facility can be found in ref. [26]. The VMS has a six degrees-of-freedom large amplitude motion base. The interchangeable cab is mounted on a carriage whose motion in the vertical axis is ±30 feet, lateral axis, ±20 feet, and longitudinal axis, ±4 feet. In addition, the cab has three angular motion degrees-of-freedom. Vibration cues through a seat-shaker system and aural cues, are also provided. The computer generated imagery scenes are displayed in the cab through four collimated CRT windows. The visual simulator system used for the AH-64A Apache on the VMS was the Singer-Link DIG-1 for most applications. The Evans & Sutherland CT5-A was also used for some piloting tasks.

During the initial Ames AH-64A Apache simulation conducted in 1989, a series of piloting tasks were performed to assess the fidelity of the simulation, ref. [27]. The piloting tasks chosen covered nearly the entire range of the helicopter flight envelope. The tasks included ground modes of operation, hovering maneuvers, low level flights, NOE flights, high speed cruise flights, banked turns, and approach and landings. Both normal and degraded visual environments were used to obtain pilot ratings. Pilot ratings for various simulation aspects were obtained, which included field of view, flight model, vibration model, computer generated imagery scene, IHADSS (Integrated Helmet and Display Sight System) operation, aural cueing, motion cueing, cockpit controller and cabin environment.

Pilot ratings and comments pertinent to the flight model were studied to identify potential upgrades to improve fidelity. For the purpose of obtaining overall pilot subjective assessment of the AH-64A Apache FLYRT simulation, different tasks evaluated were grouped into four flight regimes: ground mode, hover, low speed, and high speed. The averaged HQR's compiled form ref. [27], for both DASE-off and DASE-on flights, are tabulated below:

Modified Cooper-Harper Handling Qualities Ratings
Adequacy/Work Load

Tasks	DASE-Off	DASE-On
Ground Mode Tasks	N/A	4.7/4.65
Hover Tasks	5.9/5.35	5.2/5.3
Low Speed Tasks	6.2/5.8	5.9/5.25
High Speed Tasks	5.2/4.6	3.5/3.25

The HQR's for most of the flight tasks are in the level-2 category (deficiencies warrant improvement), except for the high speed DASE-on tasks which are in the level-1 category (satisfactory without improvement). The actual AH-64A Apache helicopter with DASE-on has a level-1 acceptance for all piloting tasks. Model upgrades for future AH-64A Apache simulations on the VMS are expected to be incorporated to improve pilot ratings.

5. SUMMARY AND CONCLUSIONS

Based on the flight model description, validation results, and applications presented, summary and conclusions along the three major areas addressed in the paper are provided.

5.1 Flight Simulation Mathematical Model

The McDonnell Douglas Helicopter Company's FLYRT flight simulation model is developed based on a comprehensive mathematical formulation. Dynamic couplings between components and mutual interference/interactions between aerodynamic surfaces are modeled. Rotorcraft components are modeled in detail to simulate the complete flight envelope. Conclusions on component models are:

1. The rotormap main rotor model is computationally efficient and is used for real-time piloted simulations using existing low-power computers.
2. The blade element main rotor model is formulated based on normal modes, to model different types of rotor blade retention systems. It has the degrees-of-freedom required for the rotor/body/drive train dynamic coupling model.
3. The fuselage model represents ±180 degrees of angles-of-attack and sideslip angles to model aircraft attitudes in all flight conditions.
4. The anti-torque module has provision to model either a conventional tail rotor/vertical tail or an advanced anti-torque system.
5. The AH-64A Apache landing gear model is a realistic representation for landing, take-off, and ground mode operations.
6. The engine models are in sufficient detail both for manned simulations and engineering applications.
7. The AH-64A Apache automatic flight control system, DASE/BUCS and horizontal stabilator, is modeled in complete detail. Necessary interfaces with cockpit hardware switches are provided for manned simulation.
8. Large attitude maneuvers such as loops and rolls are simulated without encountering singularities, since Euler angles are computed in quaternions.
9. The "paper pilot" software in FLYRT is used to simulate any desired maneuver to perform model validations and to support rotorcraft design and development.

5.2 Flight Model Validation

The rotormap FLYRT flight model is validated extensively against the AH-64A Apache flight test database. Validations include steady state trim, time history correlations for step/doublet inputs in individual axes, one engine inoperative fly-away from hover, and frequency domain validations.

5.3 Flight Simulation Applications

Applications of FLYRT simulation presented include design support, safety of flight for envelope expansion, aerodynamic component redesign, engine/airframe integration, and manned simulations. Conclusions based on specific applications are:

1. The power-off emergency landing procedure is validated against the OH-6A Cayuse flight test database. The procedure is used to establish the autorotative inertia requirements of a helicopter rotor design.
2. Simulation support during the AH-64A Apache empennage redesign established the FLYRT flight model as a reliable design tool within MDHC.
3. The terrain avoidance maneuver procedure is validated against the AH-64A Apache flight test. The procedure is used to verify the load factor capabilities of new rotor designs for pull-up/push-over maneuvers.
4. FLYRT is used to simulate air-to-air combat maneuvers to provide design support and pilot decision points for safety of flight.
5. FLYRT simulation is used for advanced control law development, both in the nonreal-time mode and in manned simulators.
6. The blade element rotor model in FLYRT, along with the single degree-of-freedom drive train model, is used to predict engine response within acceptable limits for uncompensated maneuvers which are critical for engine/airframe integration.
7. FLYRT is used in McDonnell Douglas Helicopter Company's full mission simulators for engineering applications. An AH-64A Apache FLYRT model is operational on the NASA/Ames Vertical Motion Simulator for the U.S. Army, to study accident investigations.

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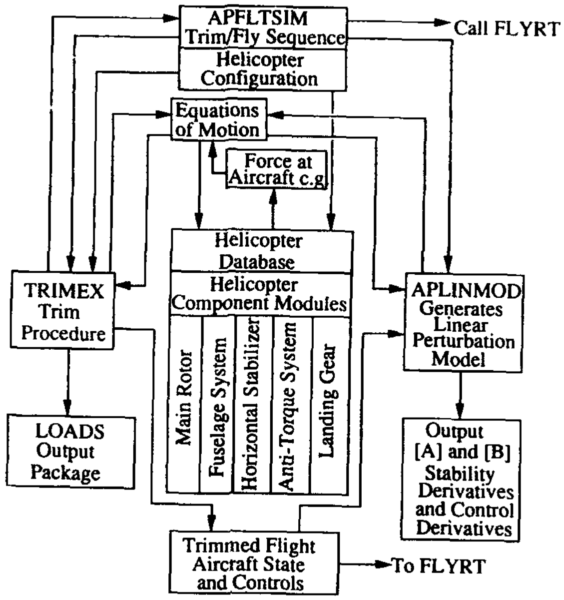


Figure 1. FLYRT Trim Procedure and Linear Model Generation

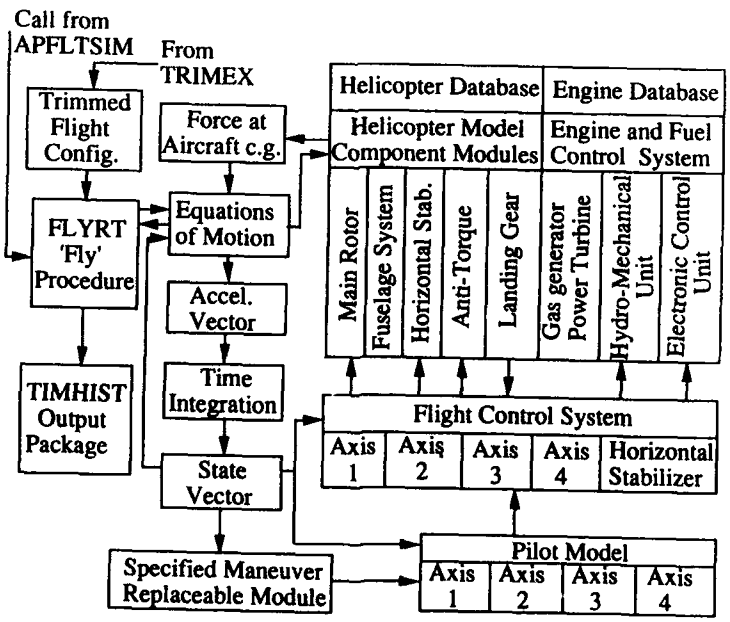


Figure 2. FLYRT Fly Sequence - Batch Version

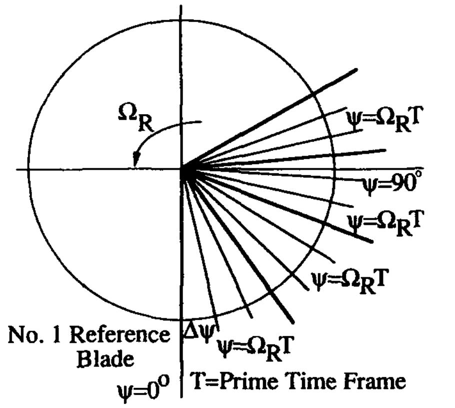


Figure 3. Blade Element Main Rotor "Fly-to-Trim" Procedure

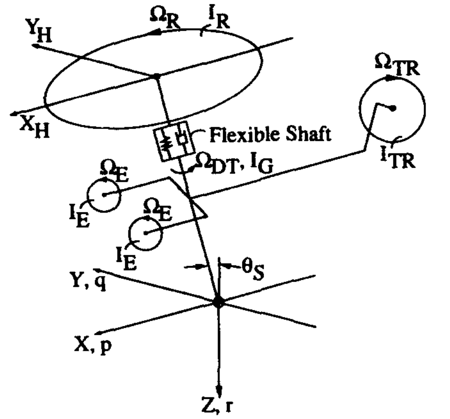


Figure 4. Main Rotor/Body/Drive Train Dynamic Coupling

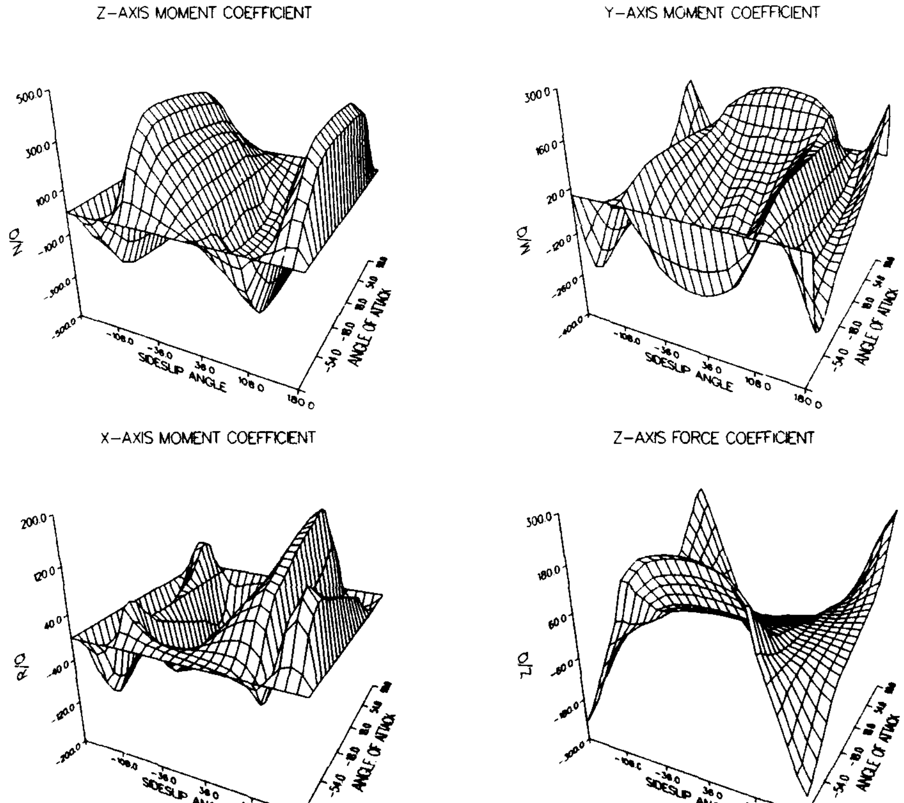


Figure 5. Fuselage Aerodynamic Data Representation

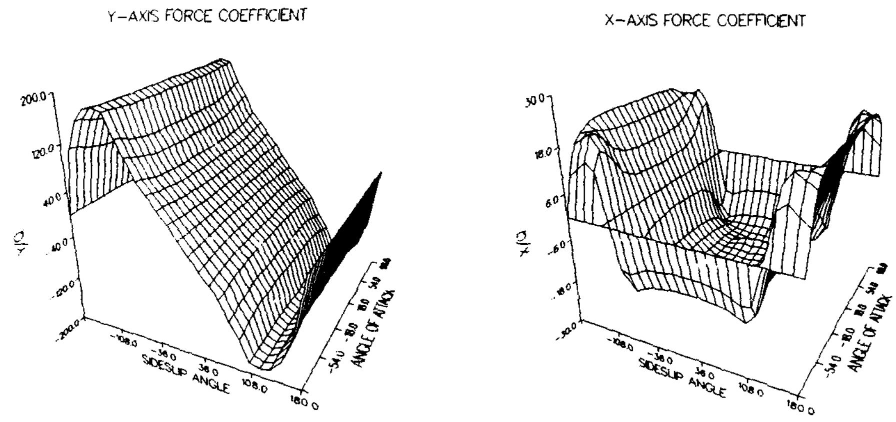


Figure 5. Fuselage Aerodynamic Data Representation (Contd.)

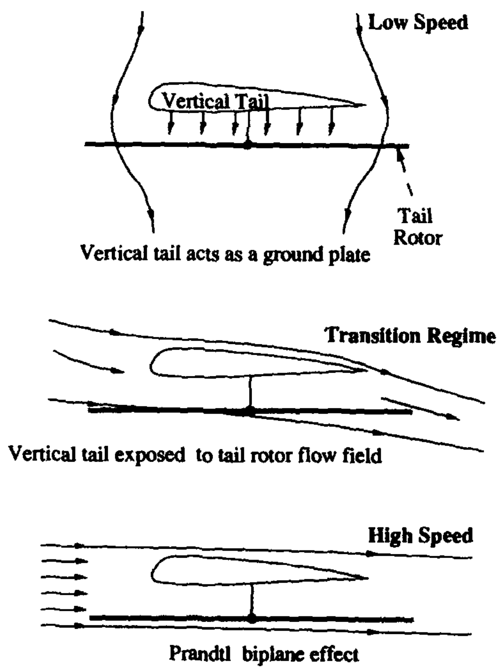


Figure 6. Tail Rotor/Vertical Tail Aerodynamic Interactions

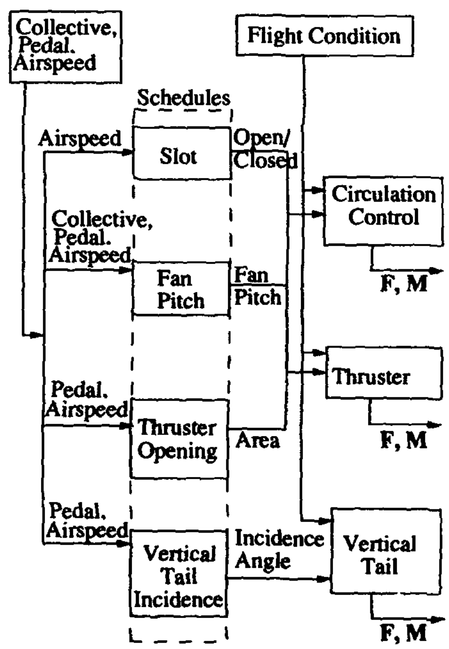


Figure 7. Advanced Anti-Torque System Model Representation

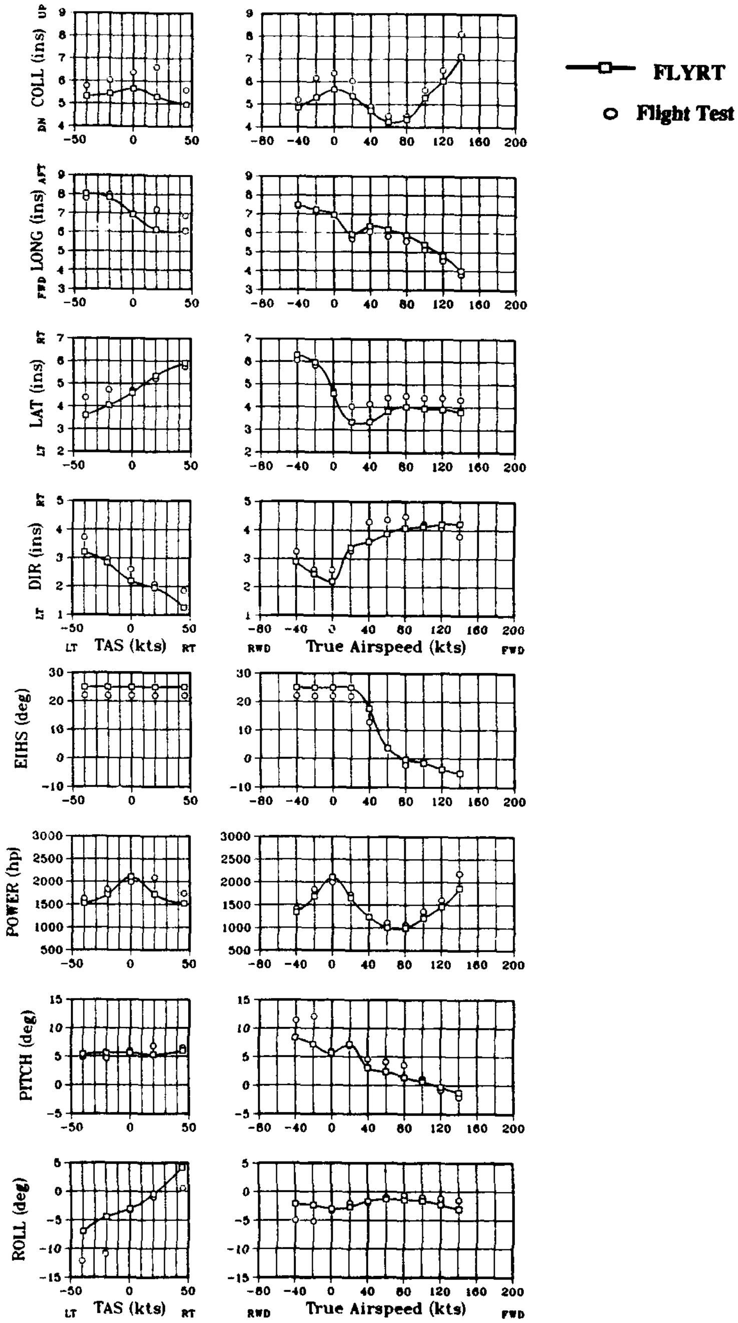
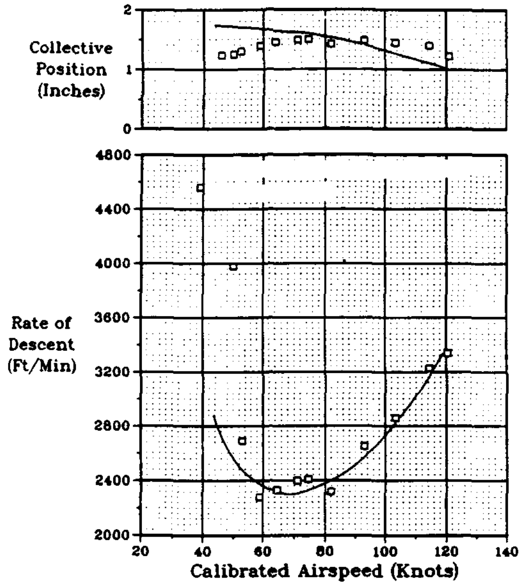


Figure 8. AH-64A Apache Steady State Trim Correlations



FLYRT □ Flight Test

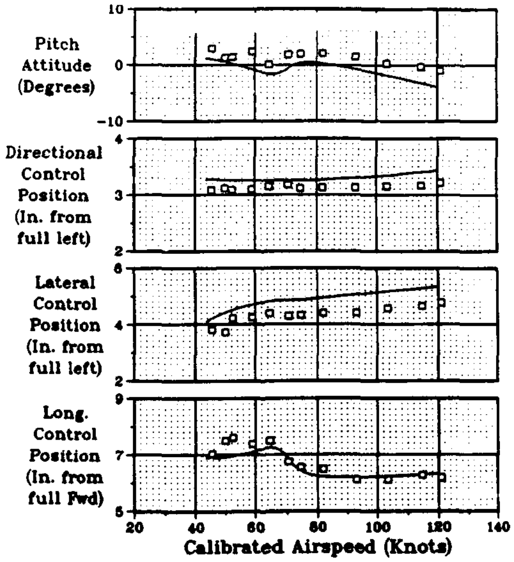


Figure 9. AH-64A Apache Trim Autorotation Descent Correlation

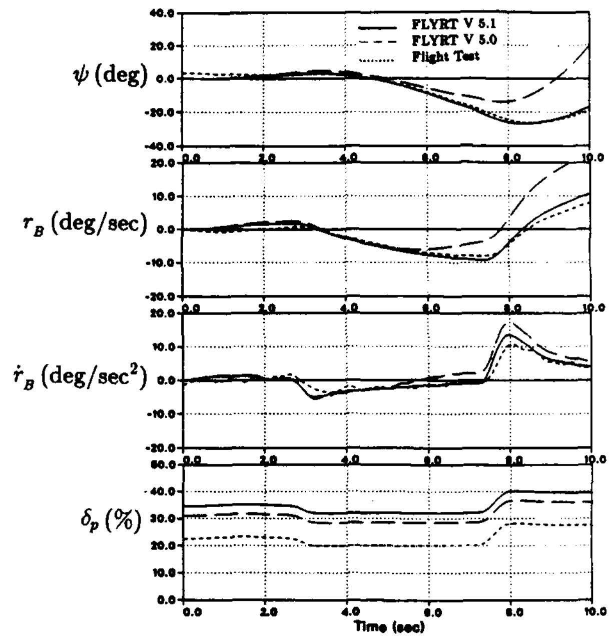


Figure 10. AH-64A Apache Dynamic Response, Directional Doublet Left, Hover

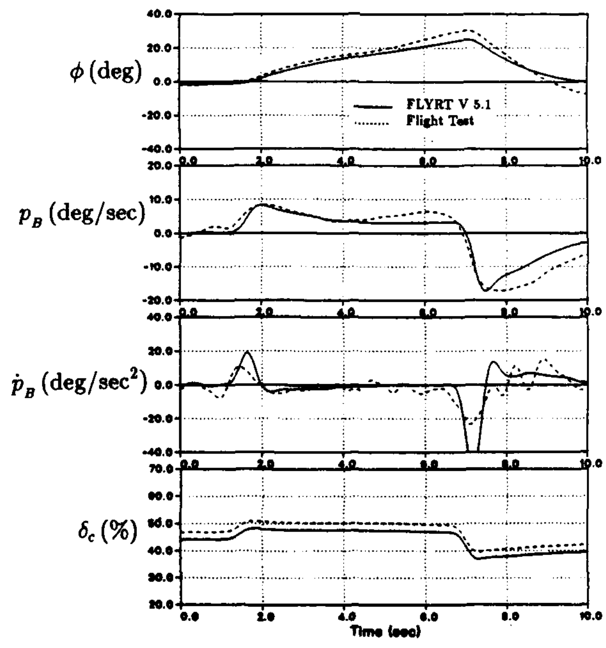


Figure 11. AH-64A Apache Dynamic Response, Lateral Doublet Right, 80 Knots

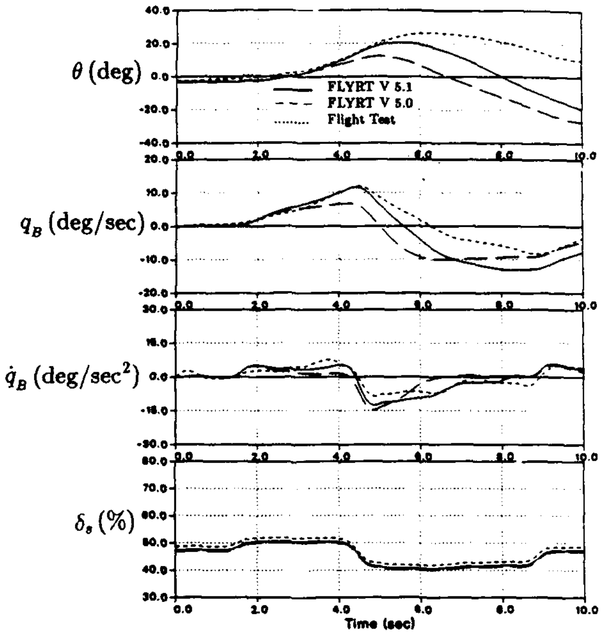


Figure 12. AH-64A Apache Dynamic Response, Longitudinal Doublet Aft, 130 Knots

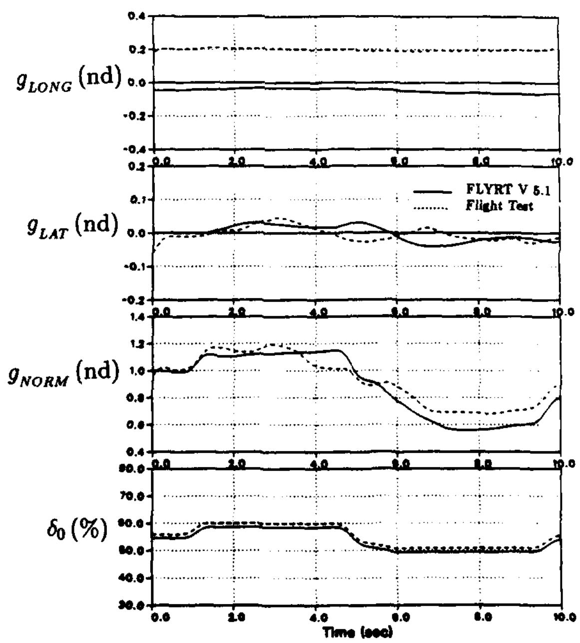


Figure 13. AH-64A Apache Dynamic Response, Collective Doublet Up, 130 Knots

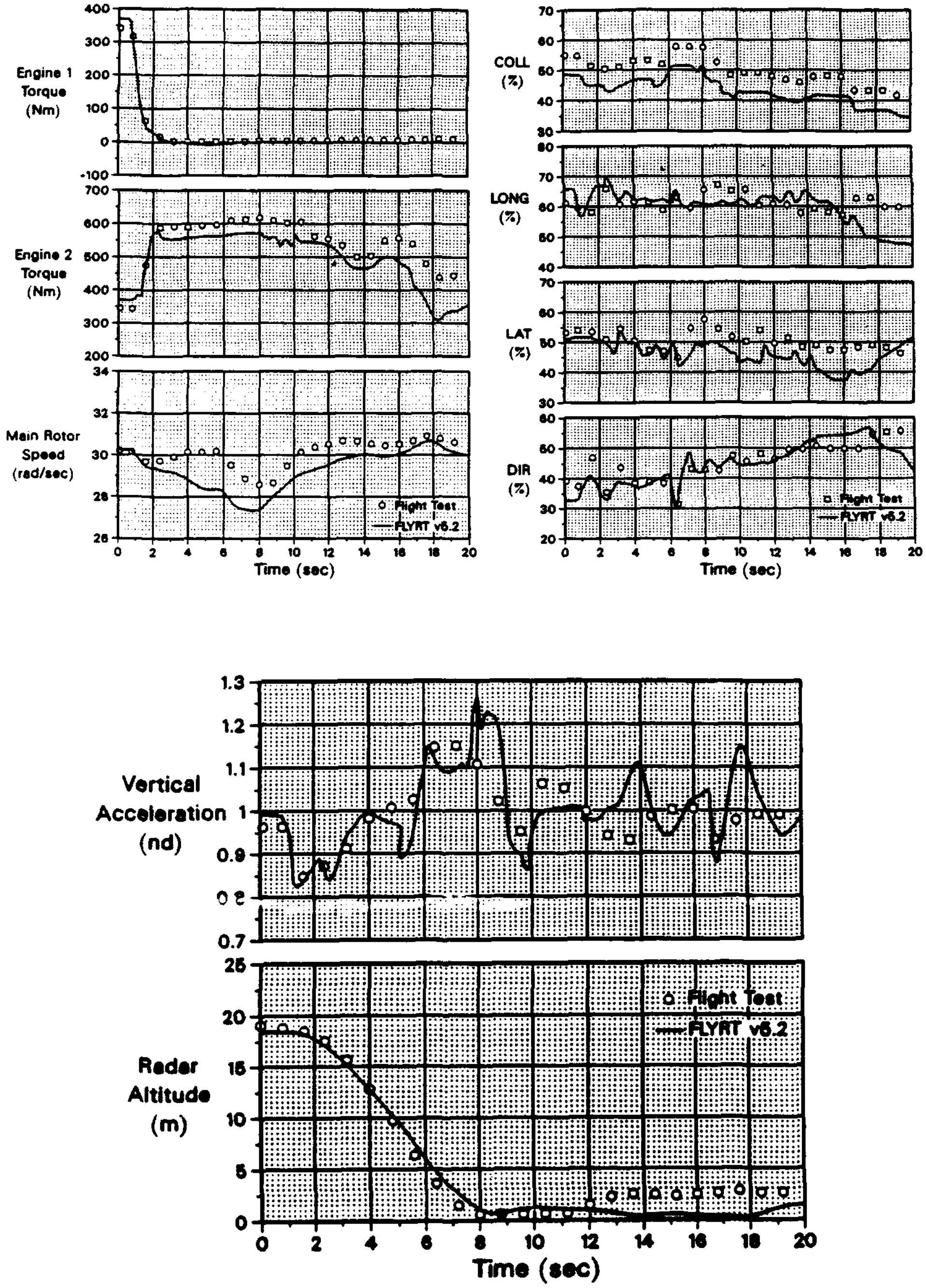


Figure 14. AH-64A Apache One Engine In-operative Fly-Away from Hover

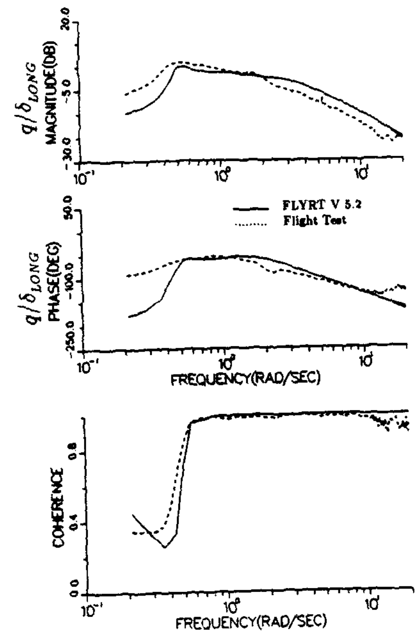


Figure 15a. AH-64A Apache Frequency Pitch Rate Response, 130 Knots

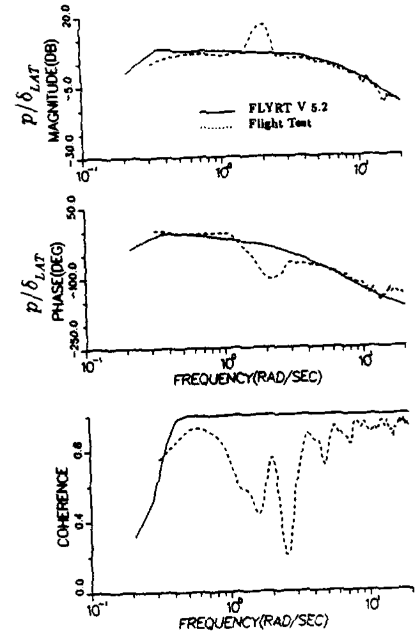


Figure 15b. AH-64A Apache Frequency Roll Rate Response, 130 Knots

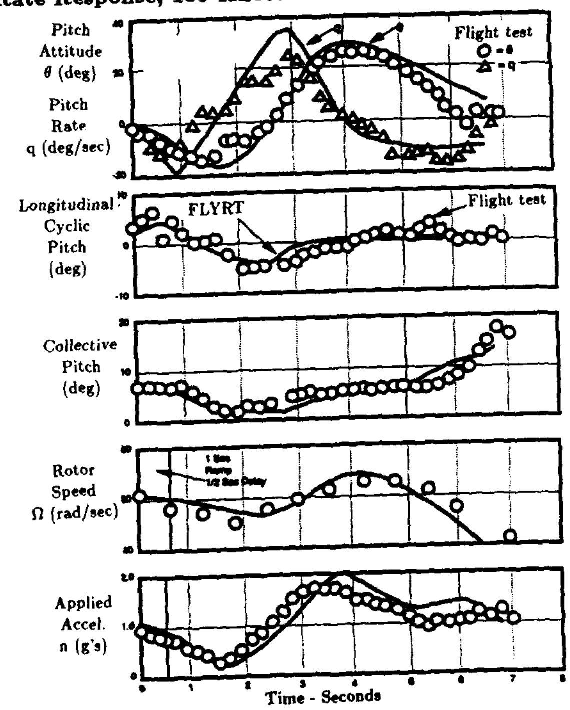


Figure 16. OH-6A Cayuse Power-off Landing from 50 Knots

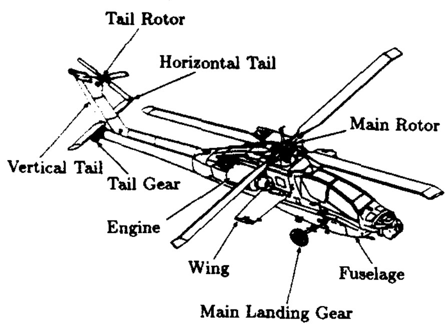


Figure 17a. AH-64A Apache Helicopter Production Configuration

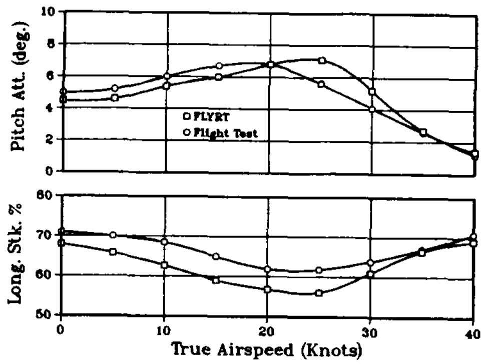


Figure 17b. AH-64A Apache Helicopter Longitudinal Trim, Level Flight Horizontal Stabilator at 35 Deg.

(Figure 18 is in the Next Page)

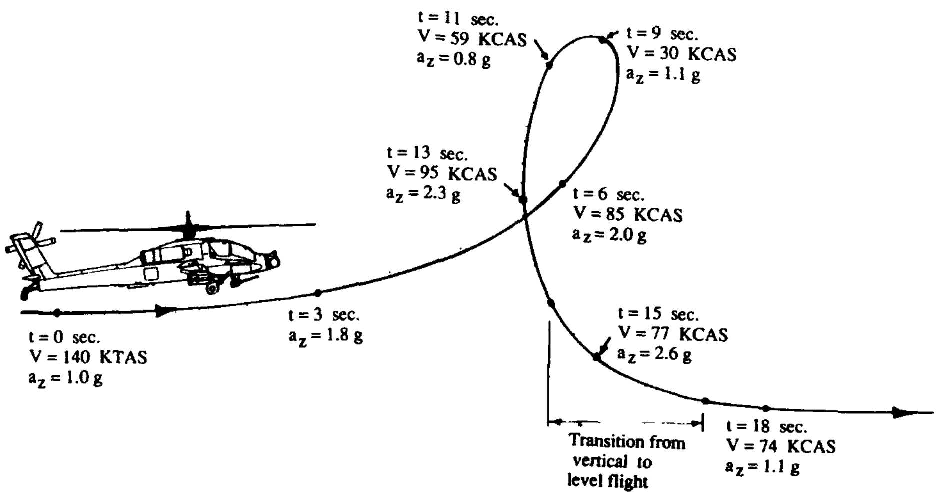


Figure 19. AH-64A Apache Aerobatic Maneuver - Vertical Loop

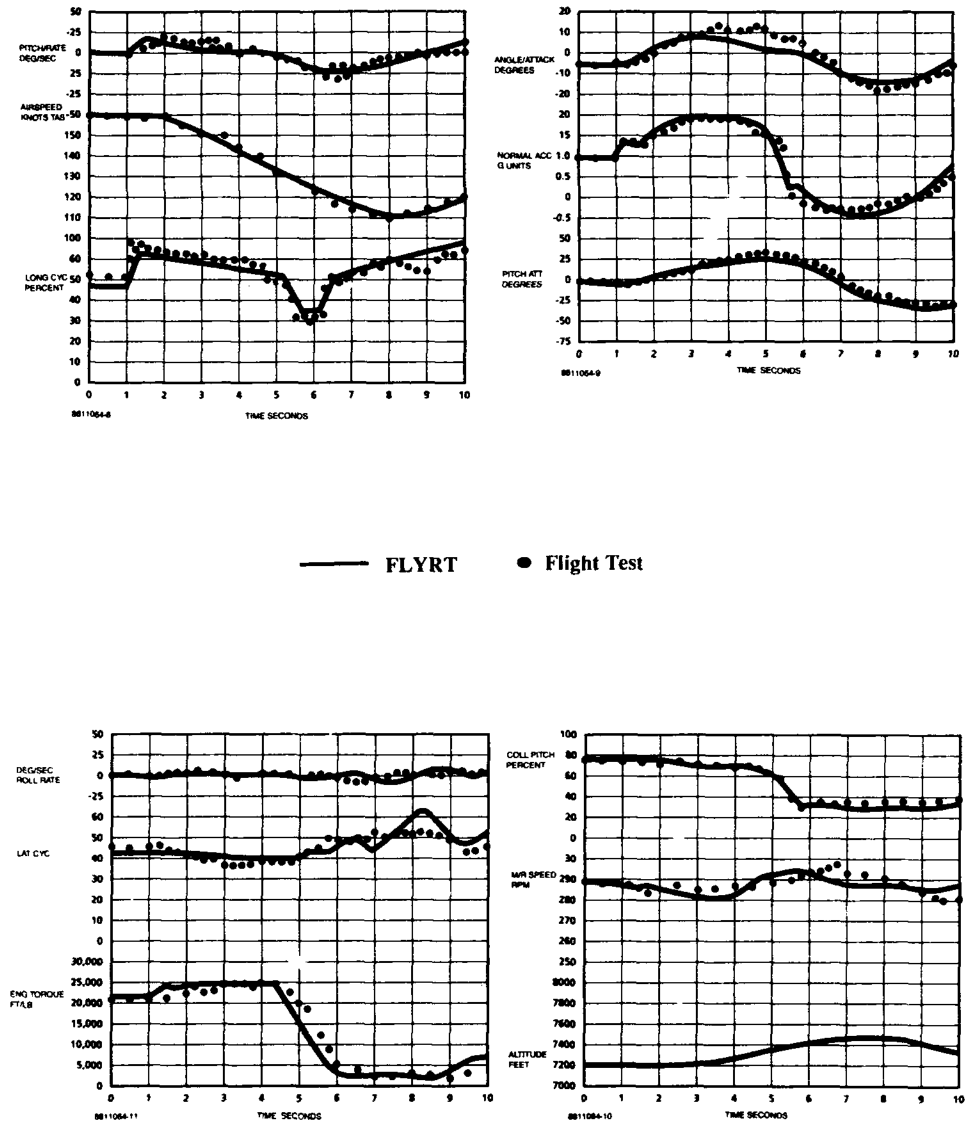


Figure 18. AH-64A Apache Terrain Avoidance Maneuver

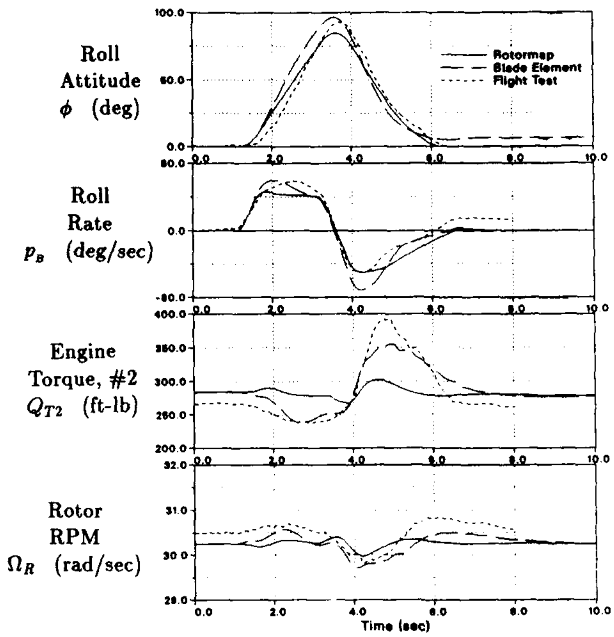


Figure 20a. AH-64A Apache Rapid-Roll Maneuver, Right-to-Left, Engine Response

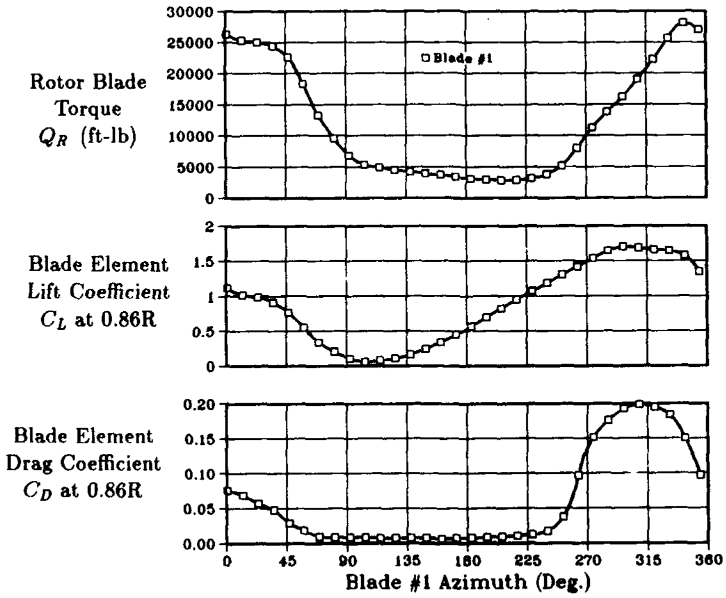


Figure 20b. AH-64A Apache Rapid-Roll Maneuver, Right-to-Left, Blade Response

Experience with Piloted Simulation in the Development of Helicopters

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Summary

Based on examples from several projects this paper reflects MBB's experience with applicability, limitations, acceptance, and effectiveness of helicopter simulation. Some of the key points are the objective and subjective validation of a simulator and the various factors, which influence the acceptance by pilots. In this context it is very important to make a trade-off between simulator sophistication (i.e. cost) and required result i.e. design input in the actual phase of development. Other aspects of simulation effectiveness include evaluation and training of critical flight conditions prior to flight tests as well as involving the customer from early concept studies up to full mission simulations, which gives him more influence on the design and leads to better identification with the product.

The paper is concluded with a summary of "do's" and "dont's" in piloted simulation to achieve maximum simulation effectiveness.

1. Introduction

In the light of increasing complexity of modern helicopters, resulting in more and more testing effort for development and certification, the piloted simulation gains a significant role. However, it is mandatory to clearly specify the areas, where this sophisticated tool has to be applied to generate design inputs and to gain confidence and acceptance, which are otherwise difficult to achieve prior to flight tests.

The intention of this paper is to sum up MBB's eperience with piloted helicopter simulation and to give guidelines for an appropriate use of simulation tools. This includes a discussion, in which areas of helicopter development piloted simulation is a must, where it is advantegeous for a development programme, and where the use of complex simulators has less beneficial effects in terms of time, cost and design input. Such conclusions can only be drawn in connection with aspects such as simulator sophistication and appropriate preparation of a simulator campaign.

2. MBB's Simulation Tools

Since 1982 five helicopter simulation cockpits have been built and used at MBB. They are in different stages of application and imply some variation of design philosophy.

2.1 BO105 Cockpit

The BO105 cockpit is actually a complete fuselage including skids. It was modified from a flight-worthy helicopter to MBB's first helicopter simulator cockpit in 1982. It had a reduced set of standard instruments and was operated in connection with MBB's Fighter Division simulation facility with a DENELCOR HEP computer with parallel processors and a GENERAL ELECTRIC Compuscene II 3-channel beamsplitter vision system (Fig.1).

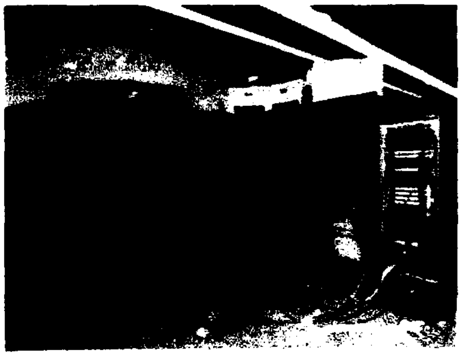

Fig.1 : BO105 Cockpit in Beamsplitter Vision System

At that time the cockpit was used for validation of the generic simulation program based on BO105 flight test results. The background for these activities were first parametric simulation studies of the NH90 transport helicopter.

2.2 PAH-2 Cockpit (1-Man)

In the pre-development phase of the PAH-2 anti-tank helicopter a 1-man simulation cockpit (Fig.2) was built with conventional instruments. This cockpit was already suitable for the 6-channel GE CIV dome vision system, which some time later replaced the 3-channel beamsplitter.

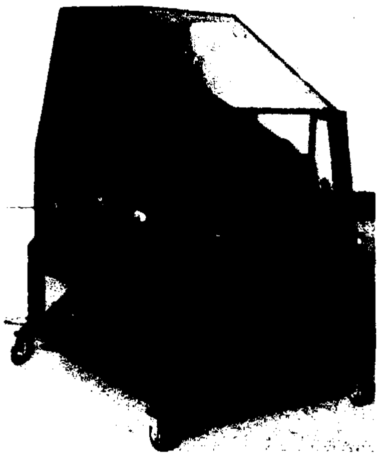

Fig.2 : PAH2 1-Man Simulation Cockpit

The main objectives were preliminary studies of handling qualities during various "Mission Task Elements" without and with control and stability augmentation system (CSAS).

2.3 BO108 Cockpit

The BO108 cockpit (Fig.3) was built as a "generic" simulation cockpit with the approximate dimensions of the BO108 helicopter and with conventional and side-arm controllers.

Fig.3 : BO108 Cockpit with Sidearm & Conv. Controls

The main objectives were studies of advanced control and display concepts.

2.4 NH90 Cockpit

In the "Preliminary Design Phase" of the NH90 a cockpit mock-up was modified into a "Basic Cockpit Simulator" (Fig.4). It was equipped with two standard airliner CRT displays with modified symbology for helicopter applications. A set of "Active Sidearm Controllers" (SAC) was installed in the pilot's station.

Fig.4 : NH90 Cockpit with Sidearm Controllers

The main objective were feasibility studies of the sidearm controllers in typical mission phases.

2.5 PAH-2 Cockpit (2-Men)

When the full development phase of the PAH-2 had started, it was decided to build a tandem simulation cockpit (SimCo) with the original dimensions and realistically simulated equipment (Fig.5). The symbologies of its 4 Multifunction Displays (MFD) are generated by 4 Silicon Graphics computers.

Fig.5 : PAH2 2-Men Cockpit (SimCo)

While all 4 cockpits mentioned previously were directly depending on a larger simulation facility (central simulation computer and sophisticated vision system) SimCo was designed to offer a stand-alone simulation capability. Since the initial application of SimCo was the development and assessment of the man-machine interface aspects of the Tiger cockpit, it was decided to install a limited computer capacity into the cockpit itself to stimulate the cockpit instrumentation by a simplified helicopter flight model. For applications beyond stand-alone or "part-task" simulations the cockpit can be linked through a VME interface to the central simulation computer and further to the dome vision system (Fig.6).

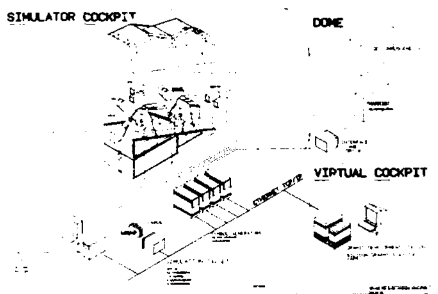

Fig.6 : SimCo Layout

This allows "combined-task" or mission simulations with full flight dynamic and system simulation in a more realistic scenario to generate a representative workload of the crew for further assessments in an advanced development phase.

2.6 Dome Simulation Facility

As indicated before MBB has erected a dome simulation center at the Fighter Division both for fixed wing and helicopter simulations (Fig.7).

Fig.7 : MBB Dome Simulation Facility

The GE Compuscene IV computer generated image (CGI) is projected in 6 channels from outside into the dome, which gives an field of view of 140° by 110° and an obstruction-free interior of the dome. As visual database helicopter simulations mostly use the so-called "Enhanced Area" of about 15 by 15 nm (Fig.8).

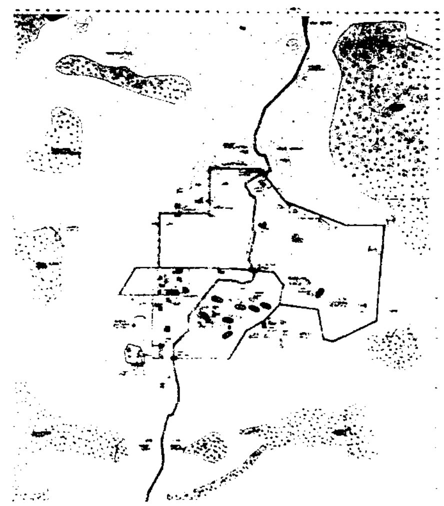

Fig.8 : Map of "Enhanced" Simulation Area

Fig.9 gives an example for the 3-D features such as houses, trees, streets, trucks, helicopters etc. in a day-light out-of-the window scene.

Fig.9 : Daylight Scene in "Enhanced Area"

For mission simulation tasks (e.g. in the Tiger programme) a second eye-point with a simulated sensor image can be generated. Fig. 10 gives an example for a low-light-level TV image.

Fig.10 : Simulated Low-Light-Level TV Image

The central simulation computer is a HARRIS Nighthawk, where presently the generic helicopter simulation programme GENSIM makes use of up to 4 (out of 8) parallel processors for the calculation of the fuselage, empennage, engines, automatic flight control system (AFCS), landing gear and blade element model of the rotor(s).

3. Simulator Validation

Besides other aspects such as training or flight test support, the main purpose of a development simulator is to generate design inputs in a programme stage between paper studies and flight tests. This requires a thorough validation of the simulator for 3 reasons:

- to give the pilot a realistic environment for a representative assessment of certain system characteristics
- to avoid wrong conclusions from simulations and hence wrong design inputs
- to gain cooperation of the pilot, because he has the impression, the simulator behaves like the "real thing" and is not only a "toy for the engineers"

Hence validation plays a key role and must be split in 2 equally important parts : "objective" and "subjective" validation, where "objective" (type-)validation can of course only start with flight tests.

1 "Objective" Validation

Since engineers are used to analytical and abstract thinking, they are very often tended to believe that they have validated a simulator objectively, when they have done their "homework" by comparing and adjusting their computer results with test data. Of course it is essential to check the flight model in terms of trim values, control response characteristics, stability etc. (see Fig.11).

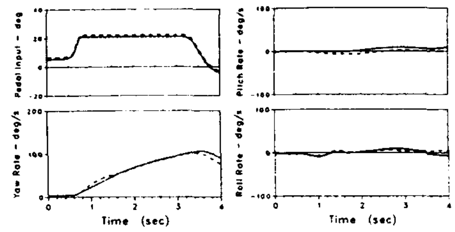

Fig.11 : Simulator Validation - Hover Turn

However, it is very difficult to validate even in an objective manner. There are various constraints mostly dictated by time and cost considerations but also by the complexity of helicopter physics:

- Only a very limited number of flight cases out of the complete flight enevelope can be studied, which can leave model deficiencies in highly non-linear conditions such as hover manoeuvres with extreme variations of incidence and sideslip angles completely undetected.
- Very often reliable test data do not exist in flight phases interesting for simulation, because they are difficult to stabilize or even dangerous to fly.
- In comparison to conventional fixed-wing aircraft it is much more difficult to predict flight characteristics of a new helicopter, even if the same simulation programme is validated with test data of existing helicopters. Some of the reasons are limited possibilities of windtunnel tests and the extreme aerodynamic environment of the helicopter in terms of interferences, Mach number and high incidence angle effects.
- Since validation runs are normally made with the simulation software in off-line mode, real-time simulation effects such as time delays with the resulting loss of stability and phase margins are difficult to detect.

3.2 "Subjective" Validation

From what is said above it may now be understood, why the terms "objective" and "subjective" validation have to be used very carefully. Even in the most sophisticated simulator a pilot will never have identically the same impression as in the real helicopter. Under the assumption that the engineers have done their homework as described above, there are still areas, which lead to unfavourable ratings of some or all pilots. It is well known from literature that Cooper Harper Ratings

(CHR) tend to be worse in simulators in comparison to real helicopters. Beyond "objective" model deficiencies some of the reasons might be:

- Insufficient vision cues:
  Even if the field of view is large enough for peripheral vision, there is still a technology gap in CGI systems, which is especially affecting helicopter simulation. Whereas in reality e.g. a grass field shows more and more details as closer one comes to the ground, CGI texture, which looks brilliant from higher altitude, looses contrast and seems out-of-focus with decreasing height. Other important visual cues are the rotor downwash effects on leaves, grass, water etc.

- Motion cues:
  Even the largest and most sophisticated simulator motion base cannot reproduce the exact motion feeling of the real aircraft. In this context it should be added that a motion base increases the complexity of a development simulator not only in terms of cost and the well known vision-motion synchronisation problem, but also in the need to compensate the lack of g-capability of the motion base by modification of the calculated model response; in other words: the unknown helicopter reaction has to be amplified by an unknown factor to use the motion base capability to the maximum extent possible.

  However, there is no doubt that a good motion system increases the realism significantly. The only question - in development simulation - is, which investment is necessary for which additional design input.

- Aural cues:
  Some essential parameters such as rotor RPM in autorotation or blade loading in high-g manoeuvres are sensed by the pilot not or not only by visual or motion cues but also by aural cues. Simulator fidelity is not much increased by additional visual indicators for such parameters (e.g. a g-meter), because pilot's attention is distracted from other tasks. Hence sound simulation, which can also be used to simulate a scenario with a more realistic stress level or workload, is a relatively inexpensive way to increase simulator fidelity.

- Pilot's background:
  A very important parameter affecting subjective validation i.e. simulator acceptance by a pilot is his own background. Especially in the area of development simulation pilots need the ability to concentrate on the parameters to be assessed without being distracted by effects secondary for the scope of the simulation study. Another aspect is the personal experience with (development) simulators, which can even lead to a preconceived opinion based on earlier negative experience. Unfortunately, there is not even a clear connection between flying experience and simulator aptitude; sometimes private pilots can manage a simulator better than test pilots with thousands of flying hours, when they are suffering from simulator sickness.

4. Examples of MBB simulation trials

Since the aim of this paper is to give some guidelines for successful simulation studies in helicopter development, it might be interesing to mention some of the experiences made in actual project work.

4.1 BO105 and LTH

As already indicated in paras 2.1 and 2.4 NH90 simulation studies started relatively early at MBB. In fact, the preliminary studies of the LTH - one of the two German NH90 versions - were the kick-off project for MBB's real-time helicopter simulation activities. They were performed with the BO105 cockpit in connection with the simulation facility of MBB's fighter division (see Fig.1).

At that time (1983) the main interest were the handling qualities of this medium size transport helicopter under variation of certain design parameters such as blade mass and stiffness, empennage size and others.

Since MBB had to prove the fidelity of the generic simulation programme, the evaluation pilots - from industry, government test establishment and operational units - insisted on the validation with BO105 flight test results (Fig.12). Since this task was the very first

Fig.12 : BO105 Helicopter

helicopter simulation in the new simulation facility (with a prototype version of the Denelcor HEP computer !) the engineers stood under ernomous time pressure fighting with untested hard- and software in a government programme with a fixed deadline. However, after some initial problems with "objective" and "subjective" validation, the BO105 model was well accepted in a relatively large flight envelope including nap-of-the-earth flight.

In this case time pressure might have helped, because there was virtually no time for a thorough off-line validation so that validation was mostly done in real-time, thus revealing all those specific problems (see 3.1).

There were 2 points with negative comments, which could not be solved with the given hardware: missing pedal force gradients (no control force simulation in yaw) and insufficient visual cues in hover and dolphin manoeuvres (only 26° vertcal field of view and no texturing).

It was very interesting to observe the psychological part of validation. Even among industry test pilots with very similar BO105 experience validation results varied significantly. While one pilot with extensive IFR experience could fly the simulator with minimal "training" time in IFR but also in typical VFR manoeuvres like hover, another pilot with mainly VFR background had even problems in cruise flight conditions.

After these BO105 validation trials the LTH/NH90 simulation runs started. These revealed a principal problem of handling qualities simulation in the pre-development phase of a helicopter project:

What to do if th imulation model (without stability augmentation) **be es in an unpleasant manner,** inspite of a careful off-line layout of essential parameters based on well established control and stability criteria ?

First (self-confident) answer:
Give the pilot sufficient time for training!

Since the LTH should become the successor of the Bell UH-1D, troop pilots were normally used to fly an helicopter with a 2-blade teetering rotor resulting in a much less crisp control response than a BO105 type hingeless rotor, which was envisaged for the LTH at that time. Hence an experienced troop pilot was initially totally overreacting with severe PIO problems. When he first gave up, another (junior) troop pilot with BO105 experience was allowed to enter the cockpit. His comment (even in hover) : "Fantastic! You must have installed a very good autopilot!" After some time the first pilot tried it again - and could fly! He thought that meanwhile an autopilot had been installed - but nothing was changed!

Second (less self-confident) answer:
Change essential parameters, but keep track!

Though it is one of the main advantages of a generic real-time simulation program, an "on-line" parameter variation is very dangerous. On one side it is easy to loose track of the base-line configuration and on the other side it is often difficult to predict, whether this unpleasant behaviour is caused by the helicopter configuration or by a deficiency of the simulation model. In the case of the LTH simulation there were finally only two main points of concern: too strong pitch reactions and insufficient tailrotor control range.
In such an early stage of a development programme with only preliminary aerodynamic data of fuselage and empennage it is very difficult to differentiate between data/model problems and configuration deficiencies.

However, the LTH project was finally a successful start of MBB's helicopter simulation activities. The customers appreciated especially, how fast the simulation model could be modified, when they wanted to study the influence of parameter changes.

4.2 NH90

Based on the experience in the LTH simulation trials it was decided some time later to continue NH90

Fig.13 : NH90 Helicopter

simulations (Fig.13) with the new NH90 cockpit (Fig.4) and the dome vision system (Fig.6). The objective was to evaluate the active side-arm controller (SAC) concept under approx. 15 realistic mission task elements. These started with gentle IFR type cruise and approach phases and ended with aggressive tactical nap-of-the-earth slalom and dolphin manoeuvres around obstacles like trees or telephone poles.

The SAC principles were :

- cyclic at the right-hand side and collective at the left-hand side (pedals are conventional)

- pilot's grip force is sensed and results in a stick displacement calculated by the Flight Control Computer based on programmable non-linear characteristics incl. manoeuvre limitations etc.

- beep trim and trim release functions enable force free stick position changes with flight condition

- take-over buttons allow override function between both crew controls

- stick positions of both crew stations are electrically synchronised

- in case of blockages control is possible by pure force feel

After completion of SAC lab tests and hardware and software integration into the simulator the actual NH90 data were compiled as far as available in the Preliminary Design Phase and the simulation model was estbalished. In spite of some data uncertainties it was decided to use the NH90 data for the simulation because of 3 reasons:

- The SAC's should be evaluated under realistic dynamic conditions i.e. with control inputs and in flight conditions typical for a medium transport helicopter.

- The official pilots from transport squadrons should find an environment as realistic for NH90 as possible.

- The international industry partners should find their contributions (e.g. windtunnel results, rotor and empennage data etc.) reflected in the simulation.

However, during the simulation trials the following problems became apparent:

- The basic (real-time) flying qualities with the preliminary data were unsatisfactory and a control and stability augmentation system (CSAS) had to be developed in the simulator, because no data of the planned Fly-by-wire system were existing at that time.

- Since no dedicated Flight Control Computer was available for the simulation, the HEP simulation computer, which had already come to its capacity limit and was due for replacement immediately after these studies, had to do this task in addition to the complex helicopter simulation program. Thus, a frame time of approx. 70 ms was required, which was too slow for a comfortable helicopter simulation and reduced also the SAC dynamics.

- Due to this situation many pilots were too busy with stabilizing the helicopter and had difficulties to evaluate the SAC characteristics in isolation. Furthermore the slow frame time of 70 ms plus the additonal image generation and transport delays altogether summed up to approx. 180 ms. This aggravated the tendency to PIO problems especially in more aggressive manoeuvres.

Nevertheless, the simulation trials yielded a couple of positive results, which were mostly based on assessments of pilots used to development simulation. The ergonomy of the controllers and the crew station comfort received very positive comments. The realism in terms of vision system and mission tasks was found satisfactory. The SAC dynamics were found to be inadequate for high-gain tasks like slalom or hover manoeuvres; this could not be found out during lab tests.

Hence, inspite of the problems with the simulator handling qualities, the main objective of the simulation had been reached.

Again, some interesting observations could be made:

- One of the pilots, who had no great difficulty with the simulator, was in fact a private pilot with only very limited flight experience.

- The only pilot (out of approx. 15 during that campaign), who seriously suffered from simulator sickness, was a very experienced test pilot.

- While some troop pilots could very well concentrate on the task to evaluate the SAC's in isolation, others (some of them had their reservations even before the simulation) were distracted by missing aural and motion cues, were not inclined to follow the gradual increase of mission task complexity (because "the NH90 is a tactical helicopter and does not fly IFR type cruise manoeuvres") and were not willing to use the telephone poles as references for dolphin manoeuvres, "because a pilot will never fly through telephone wires".

4.3 PAH-2/Tiger

As indicated in 2.2 and 2.5 two different cockpits are being used for different applications and with a different philosophy. Preliminary simulation studies started in the PAH-2 (Fig.14) pre-development phase in 1985 in order to establish control ratios, necessary couplings, basic CSAS control laws and failure characteristics. All these studies were performed with the 1-man cockpit (Fig.2) and mostly in the dome.

Fig.14 : PAH-2/Tiger Helicopter

More recent simulation trials were performed in order to check the viability of some important mission element requirements such as precision hover with wind, rapid hover turns, rapid acceleration/deceleration, sidestep, bob-up/bob-down, dolphin, slalom, 180° turn, roll reversal with different g-levels and quick stop. These elements are similar to requirements in the American LH Comanche programme and are being modified for application in the Tiger programme. In spite of the well-known technical problems with nap-of-the-earth helicopter simulation (vision system, ground effects etc.) and inspite of the missing assistance by the autopilot, which still had to be developed at that time, the simulation runs with industry pilots were very fruitful to gain confidence that the requirements could be met or to arrive at more realistic values in case of too severe requirements. Since the Tiger is not equipped with a g-meter, the pilot had again difficulties to estimate and maintain a certain load factor. During these trials it was finally decided to develop a simple helicopter noise simulation in order to give the pilot at least an aural impression of the rotor state.

The first time that operational pilots performed Tiger simulations at MBB was, when the French-German Consulting Crew was invited to validate the dome simulation facility. Since the 1-man cockpit has no mission equipment whatsoever, only a low-level "reconnaissance mission" was performed, which had to be prepared with a map of the artificial database (Fig.8). The task was to find some tanks hidden behind houses or trees in the "enhanced area". Each pilot received a special briefing with a specific route shown in the map. The other pilots could monitor his mission by TV and intercom in a separate briefing room. It was unanimously stated that this simulation tool was very suitable for mission simulations and could even be used for training of operational crews.

It was already said in para 2.5 that the second cockpit "SimCo" (Fig.5) followed a totally different approach. At the start of the full development phase of the Tiger programme it became apparent that the cockpit layout, especially the controls and displays, required not only mock-up's, but also a new simulation cockpit with realistically equipment and the original tandem arrangement.

Since the task for this cockpit was primarily the development and assessment of the man-machine interfaces (MMI), it was felt to be more cost-effective to give SimCo a simplified stand-alone simulation capability instead to use always the complex dome system for even limited tasks such as basic symbology assessments. This concept proved to be right and in spring 1991 an extensive simulation phase of approx. 2 months was performed with the participation of French and German industry and operational pilots. The initial SimCo arrangement (Fig.5) was enhanced by monitoring facilities for official test observers and an 1-channel vision system (Fig.15).

Fig.15 : SimCo with 1-Channel Vision System

The trials (more than 70 hours official assessments) were very fruitful. Approx. 95 % of the defined (part-)tasks could be performed and resulted in a large amount of feed-back and proposals for modifiction of symbologies (Fig.16) and other MMI aspects. The possibility to

Fig.16 : SimCo Pilot Station

programme symbology options proposed by the pilots in a very short time for immediate real-time evaluation was highly appreciated. However, this again needed a very

careful configuration management not to loose track of the base-line configuration, which had to be the starting point for every new crew in order to have an equal basis for comments. It should be noted that we received very valuable assistance from representatives of the French Centre d'Essais en Vol (CEV) in Istres with their vast experience in official assessments.

Another positive consequence of the stand-alone simulation capability of SimCo was the opportunity for the AFCS engineers to test their control laws and especially their mode switching philosophy in a real-time cockpit environment without the cost penalty normally associated with pilot-in-the-loop simulation. Since fine-tuning of helicopter control law parameters is anyhow still the domain of flight test, there is not much more requirement for complex (and expensive) simulation, when the man-machine interface aspects (operational logics) could be tested very thoroughly in SimCo in stand-alone mode with a simple helicopter model.

It must be added here that we had a similar problem with our simplified PAH2/Tiger model in the first SimCo assessments as we had with the preliminary NH90 model in the SAC evaluation. Again the flying qualities were not as comfortable as desired for complex MMI assessments. Hence we decided to install a model for the next activities, which is easy to fly but not necessarily very similar to a particular helicopter.

The next phases of Tiger simulation will be combined-task simulations with increasing complexity of the cockpit equipment - from basic systems like AFCS, engine, landing gear, hydraulics etc. up to mission systems like visionics and armament. These activities will mostly be performed in the dome, since the crew performance under most realistic workload has to be assessed.

4.4 EUROFAR

Another recent simulation activity were studies concerning the conversion phase of the EUROFAR tilt rotor transport aircraft (Fig.17).

Fig.17 : EUROFAR Tilt Rotor Aircraft

Based on the Stability Analysis program for Convertible Rotor Aircraft SACRA (Fig.18) a real-time version had been developed, which was initially used in the BO108

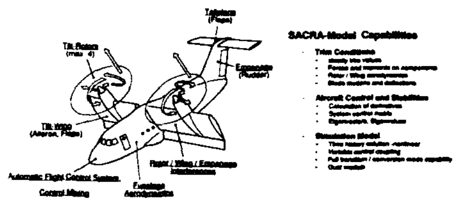

Fig.18 : SACRA Simulation Model

cockpit (Fig.3) with conventional helicopter controls and EFIS displays. Their symbology had to be slightly modified for monitoring of new parameters such as the angles of the nacelles, which were initially operated automatically as function of flight speed. Fig.19 shows the conversion corridor (with flaps at 30°), which defines the nacelle angle range as function of airspeed within the boundaries of wing and rotor stall.

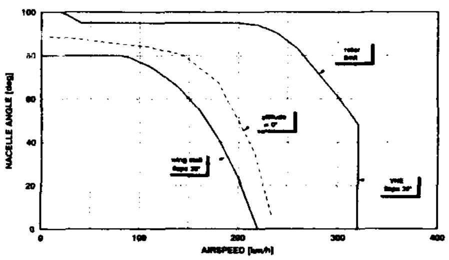

Fig.19 : EUROFAR Conversion Corridor

An example of a simulated conversion from helicopter mode to aircraft mode is shown in Fig.20. In this case

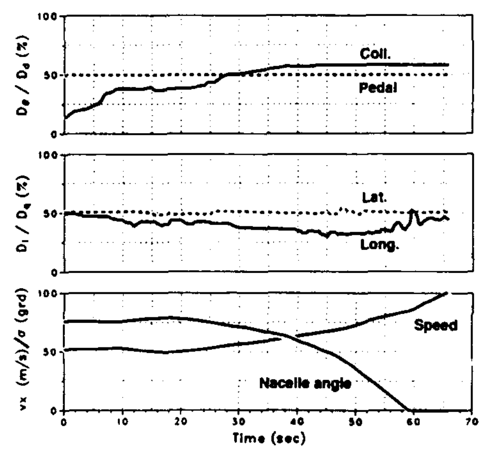

Fig.20 : EUROFAR Simulation - Transition Phase

the nacelle angle was automatically decreased from 75° to 0° and the pilot had only to control the flight path of the aircraft equipped with a basic stabilization system. In the next simulation phase the pilot will be able to control the nacelle angle by a beep switch at the power lever resp. collective pitch. He can do this within a certain boundary around the prescribed law, if he wants to accelerate or decelerate his conversion speed.

The simulator studies were very helpful for establishing the logics and control laws of the new control parameters as well as for definition of the preferred ranges and couplings of the conventional controls.

4.5 Active Control Technology (ACT)

Finally, another activity should be mentioned, where the BO108 cockpit will be used, since it has the capability of being operated with conventional as well as side-arm controllers simultaneously (Fig.3). This feature together with the flexibility of the EFIS displays allows the investigation of various advanced and conventional control concepts during pre-defined mission task elements. Since this activity is a multinational programme, it will be of special interest to compare the findings of the different teams on their different simulators and to compare the simulators with each other, based on the same simulation model.

5. *"Do's" and "Dont's" in Piloted Simulation*

From what is said above it is evident that many lessons could and had to be learnt in the past - and will have to be learnt in the future. It will never be possible to avoid problems and errors in the field of helicopter development simulation, but it might be helpful to have some guidelines, which should be used right from the beginning of a new programme. In the following these guidelines are summed up as "do's" and "dont's":

a) Don't expect the simulator to predict exactly the AFCS-off handling characteristics of a new helicopter in all flight conditions

This might be disappointing, but Fig.21 shows, why the

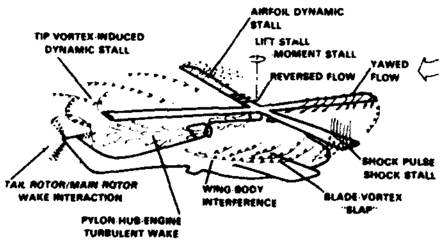

Fig. 21 : Aerodynamic Environment of an Helicopter

engineers do not have much chance to be successful. The aerodynamic environment of an helicopter is so complex in terms of stall, Mach number, vortex and interference effects that even very sophisticated models (which would be difficult to run in real-time) will not tell the full truth. Since even in the wind-tunnel many of these effects cannot really be tested, it is unavoidable to tune the model with flight test results.

This is one of the key differences between fixed-wing and rotary-wing development - besides the budgets! But how good are generic fixed-wing simulation models at incidence angles of more than say 50°?

The next rule is closely linked to the first one:

b) Don't try to finalize parameters like empennage size or control laws in the simulator

The simulator is a very powerful tool to study parameter influences on pilot's workload or to evaluate basic AFCS control laws, command models or moding philosphy. But due to the complexity of helicopter flight mechanics - and the need to use sometimes less comprehensive real-time models - it is not worthwhile to spend too much effort into fine-tuning on simulators, when you have to repeat most of the exercise again in flight test.

However this rule can also be used in a positive way:

c) Do adjust your simulation tool to your task

Since the only reason for piloted development simulation is to get design inputs from the pilot, which are not achievable from paper, one should concentrate on the "man-machine interface" aspects. These include all systems to be operated, controlled or monitored by the pilot such as flight controls, AFCS, displays, switches or other cockpit equipment. While most of the ergonomic aspects need mainly a full-size cockpit mock-up, a large part of the operational aspects needs only a relatively simple simulation set-up with just a typical stimulation of the equipment to be assessed.

Only in a later development phase or in (research) programmes, where flight simulation is essential (e.g. mission task elements), a more sophisticated simulation model and vision system is required. But also here the helicopter model should normally be so easy to fly that the pilot can concentrate on the new system to be assessed instead of "fighting with the simulator".

A special case is the requirement to simulate the effect of partial and complete AFCS failures on mission performance. This doubles the challenge for the engineer, because both conditions - AFCS-on and -off including transients - have to be simulated realistically.

d) *Do listen to the pilot carefully*

There are many examples, where the simulation engineers could fly their simulator "better" than an experienced test pilot. But besides the fact that some pilots are really not "made for simulation", most of them will have good reasons for their critical comments. Sometimes these comments are not in line with the ideas of the engineers, but normally it pays off to incorporate the pilots' proposals and to give them the impression that their remarks bear fruits. This will not only improve the simulator but will also help that the pilots feel responsible for it and identify themselves with it. An example: it might be more important for the pilot to have an additional simple cue (e.g. rotor noise) or another instrument (e.g. engine torque) than to spend much more effort on sophistication of the software.

In the same context it should be mentioned that a pilot will not be convinced with results of an "objective" validation as long as he has not validated the simulator "subjectively". On the other hand it is mandatory to keep track of all the desired modifications, because it happens quite often that the very first configuration is finally rated the best. Another reason for careful configuration management is the need to be able to present the same base-line status to all evaluation pilots in one particular phase.

Since it is essential that the most important man in simulation - the pilot - accepts the simulator and is willing to work with it efficiently, there is another important rule :

e) Do spend enough effort on preparation

Besides a careful validation, this mainly applies to the scenario, which should be as realistic as necessary, and even more to the briefing and debriefing procedure. Depending on the complexity of the task and the tool, the briefing and familiarization phase can take hours. For better cost-efficiency it might again be advisable, to use a "stand-alone" capability of a simulation cockpit for the briefing of a complex mission simulation in e.g. a dome vision system.

Another part of good preparation is a document, which describes the simulation set-up as detailled as necessary to understand the scope and the limitations of the planned simulation task. Here it is more essential to define the "surface" of the cockpit and the "performance" of the simulated helicopter instead of going into unnecessary details of the real-time simulation hard- and software ("number of blade elements" etc.). A remark to limitations: from psychological point of view it is often better to be a bit more self-critical and let the pilot find out that it is not so bad, instead of doing it the other way around!

6. Conclusion

The simulation in the development of helicopters is a very fascinating and challenging activity. On the other hand it can also be very expensive. By knowing its advantages and accepting its limitations, it will be an invaluable tool in a helicopter development programme. However, it will only be cost-efficient, if the hard- and software is well adapted to the real requirements of the specific task.

INTERET DES SIMULATIONS "TEMPS REEL" POUR LE DEVELOPPEMENT DE LA FONCTION SUIVI DE TERRAIN DES SYSTEMES RADAR

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ABSTRACT :

During a penetration mission, modern tactical aircrafts have to fly over regions with heavy electromagnetic environment.

To realize such a mission, a minimum knowledge of terrain elevation is needed. Terrain elevation knowledge can be obtained from real time sensor such a radar.

The development of terrain following function becoming more and more complicated, it necessitates the use of simulations to analyse the performances of sophisticated data processing and flight control.

The aim of this paper is to demonstrate the contribution of interactive real-time simulations during the phase of development to optimize radar resources management, in different types of terrain and many configurations of electronic warfare.

In this paper is then shown how the operationnal people can take part to the definition of the radar to obtain the most appropriate comportment.

It is finaly discribed how to characterize the radar performances in the complete weapon system and observe the manifestation of error stimulation on the security of the system.

RESUME

Lors d'une mission de pénétration, les avions de combat modernes doivent survoler des régions à très basse altitude dans un environnement électromagnétique dense. Pour réaliser ces missions, il est nécessaire de connaitre le terrain avec une précision suffisante. Les systèmes radar permettent d'acquérir cette connaissance en temps-réel.

Le développement de la fonction "suivi de terrain" nécessite de maitriser l'ensemble des performances des traitements retenus ainsi que le comportement du système complet et de ses éléments constituants.

Cet article présente la contribution des simulations "temps-réel" interactives lors de la phase de développement dans le but d'optimiser le système radar dans les différentes configurations répertoriées (terrain survolé, scénarios guerre électronique, météorologie, ...).

Il décrit également de quelle façon les opérationnels peuvent intervenir à partir de cet outil pour disposer de la fonction correspondant le mieux possibles au besoin.

Il est montré enfin comment ces simulations peuvent être utilisées pour l'aide à la définition du système complet.

1. INTRODUCTION

Depuis quelques années, les simulations "temps-réel" interactives, qui étaient jusqu'alors pratiquement essentiellement réservées aux simulateurs d'entrainement sont devenues des outils indispensables pour l'aide au développement des systèmes complexes et notamment de systèmes radar.

Cela est dû en premier lieu aux récents progrès de l'informatique. En effet il est possible aujourd'hui de disposer de calculateurs suffisamment puissants pour permettre l'exécution des programmes de simulation en temps-réel et possédant des systèmes de développement de plus en plus conviviaux.

De plus les moyens graphiques, qui sont de plus en plus performants, permettent aujourd'hui de reproduire fidèlement l'environnement extérieur tel qu'il est perçu par l'utilisateur et de restituer les différentes visualisations telles qu'elles sont prévues dans le radar.

Cela est dû également au fait que les systèmes à développer sont de plus en plus complexes et qu'il est nécessaire de disposer des outils les plus sophistiqués capables non seulement d'analyser les performances mais également les comportements des systèmes dans toutes les configurations prévues et tous les environnements envisagés pour réduire les coûts d'étude et de développement et la durée des phases d'essai.

C'est le cas du radar dans sa fonction suivi de terrain ; ce qui explique que les simulations temps-réel interactives soient utilisées dans son développement.

Dans une première partie est donnée la définition de simulations "temps réel" interactives pour les systèmes radar de pointe avant.

Dans une deuxième partie il est donc montré l'apport des simulations temps-réel interactives dans les différentes étapes où elles interviennent dans le processus industriel.

Dans une troisième partie il est décrit en quoi consiste le vol à très basse altitude et quelles sont les exigences de cette fonction.

Il est enfin montré l'intérêt de l'utilisation de ces simulations dans le cadre du développement de la fonction suivi de terrain pour un radar moderne.

2. LES SIMULATIONS TEMPS REEL INTERACTIVES DANS LES SYSTEMES RADAR

Les simulations temps-réel interactives occupent une place de plus en plus importante dans le domaine des radar de pointe avant. Ces simulations consistent à recréer une image du radar tel qu'il est perçu par l'utilisateur dans ses différentes fonctions au cours de missions opérationnelles.

Elles sont constituées :

- de modèles décrivant le fonctionnement de chacun des éléments constituants du système. Le modèle radar tout d'abord pour lequel on cherche à être le plus représentatif possible en ce qui concerne ses performances, son comportement et ses entrées-sorties (commandes, informations de visualisations, informations destinées au système, ...). En ce qui concerne les autres modèles la représentativité est limitée au besoin de bon fonctionnement du modèle radar ou au réalisme minimum nécessaire à la simulation complète. Ces modèles sont des modèles d'avion, de centrale à inertie, de cibles, de terrain, d'environnement atmosphérique et météorologique, de contre-mesures électroniques...

- d'un poste de commande radar permettant de sélectionner les différents paramètres de la même façon que dans l'avion,

- d'un poste de commande de simulation qui permet de choisir les paramètres d'utilisation de la simulation (formation des cibles, scénario d'interception air-air, type de terrain survolé, scénario d'émission de contre-mesures électroniques, conditions météorologiques, ...) ainsi que des paramètres internes au modèle radar pour en observer l'influence sur le déroulement de la simulation,

- des commandes permettant de mettre en œuvre le modèle avion (manche, manette des gaz, ...),

- des visualisations radar,

- des visualisations de servitude permettant d'illustrer ou de contrôler le fonctionnement du radar ou de la simulation soit en comparant les variables obtenues avec celles idéales en entrée de la simulation soit en apportant une vision complémentaire aux visualisations radar,

- une gestion globale de la simulation. La simulation est conçue pour être interactive c'est-à-dire de façon à ce que toute demande extérieure (commande radar, manche, ...) puisse être prise en compte avec un délai tel que les actions en découlant s'effectuent de façon conforme temporellement à ce qui est observable dans la réalité.

3. INTERET DES SIMULATIONS TEMPS REEL INTERACTIVES DANS LES SYSTEMES RADAR

L'intérêt de telles simulations est multiple, ce qui explique qu'elles aient rapidement pris une place nécessaire importante dans le processus industriel. Elles interviennent à tous niveaux et sous différents aspects :

- Démonstration

Tout d'abord c'est un excellent outil de promotion. En effet ces simulations permettent de montrer le produit tel qu'il est défini bien avant la sortie du matériel et donc d'en illustrer les performances et l'emploi. Elles permettent également de démontrer une capacité ou un savoir-faire par la démonstration des produits déjà existant.

- Validation de concepts

Ces simulations servent également à la validation de concept. En effet dans le cadre de fonctionnalités nouvelles, la définition de principe n'est ni forcément unique ni aisément démontrable. L'introduction de ces nouveaux principes dans les simulations permet donc d'entériner leur bien-fondé ou de donner des éléments supplémentaires pour choisir le principe le plus approprié quand les performances seules ne suffisent pas à lever l'indéterminé. Cette validation peut être réalisée tant au niveau du radar qu'au niveau du système.

- Prédimensionnement de système

Ces principes établis le fait de pouvoir disposer de modèles paramétrables permet d'effectuer un prédimensionnement du système et de réaliser ainsi les premiers compromis permettant d'obtenir une première définition de celui-ci.

- Aide à l'étude de fonctions

Les simulations interviennent également dans la phase d'étude pour la définition de certains traitements ou de la mise en œuvre du radar. Il est en effet possible de valider les traitements radar dans de nombreuses phases d'emploi de celui-ci qui ne sont pas forcément facilement accessibles avec des essais en vol (survol de terrains particuliers, reproduction de phénomènes atmosphériques, vol supersonique, ...). De même, la gestion du radar peut être définie, analysée, contrôlée et optimisée à travers l'étude de différents scénarios dimensionnants.

- Développement de l'interface homme-système

Dans la définition de l'interface homme-système c'est un outil indispensable non seulement pour l'aide à la définition des commandes et des visualisations, mais aussi pour le contrôle et la validation de leur enchainement logique, de leur exhaustivité, de leur intérêt et de leur compréhensibilité.

- Aide aux essais en vol

Dans la phase d'essais en vol ou au sol les simulations servent à prédire le comportement du radar avant la séance d'essais afin d'en assurer l'efficacité maximale et d'optimiser de par ce fait l'ensemble de la séquence d'essais. Elles peuvent également servir à préparer les expérimentateurs aux futurs essais en effectuant une répétition des vols dans le cas d'utilisation particulière du radar ou de manipulations difficiles.

- Extrapolation des essais

Une fois les essais achevés, un affinage des modèles constituant la simulation est réalisé à partir des enregistrements en vol. Il est alors possible de rejouer les essais en obtenant des résultats comparables et d'extrapoler ceux-ci à des "vols" effectués uniquement en simulation en prenant naturellement toutes les précautions nécessaires. Il est également possible de rejouer des phases difficiles à mettre en œuvre ainsi que des phénomènes rencontrés en de rares occasion.

- Intégration système

La simulation peut être réalisée également au

niveau du système. Elle permet par l'utilisation de modèle d'équipement de préparer l'intégration système en vérifiant l'exhaustivité, la validité et le bon emploi des entrées-sorties.

- Dialogue utilisateur

Ces simulations permettent enfin de familiariser l'utilisateur avec le produit, de définir avec lui les règles d'utilisation puis ensuite de l'entraîner à l'utilisation optimale de celui-ci.

4. LE VOL A TRES BASSE ALTITUDE

Le but de la fonction "suivi de terrain" est de guider l'avion afin de pouvoir survoler tous types de terrain connus ou inconnus, à une hauteur minimum au-dessus d'une hauteur de consigne sélectionnée, avec un taux de sécurité le plus important possible et quelles que soient les conditions extérieures (météorologiques, électromagnétiques, ...).

Cela consiste donc à élaborer une trajectoire devant être suivie par le chasseur. Cette trajectoire est déduite de la connaissance instantanée du terrain et de la localisation de l'avion dans celui-ci.

La bonne connaissance du terrain est donc une condition nécessaire à la bonne réalisation de cette fonction. Deux catégories de terrain sont envisageables, les fichiers de terrain embarqués et les terrains obtenus à partir de capteurs "temps-réel" comme le radar.

Le fichier embarqué, s'il n'est pas affecté par le brouillage électromagnétique, nécessite de disposer d'une localisation absolue très précise et d'avoir recensé la totalité des obstacles verticaux du terrain qui peuvent être survolés lors de la mission. La qualité du terrain est indépendante de la position avion.

Le système radar permet d'obtenir une carte de terrain au moment même du passage de l'avion sur celui-ci sans connaissance préalable de ce terrain. Il peut cependant être sensible aux pollutions électromagnétiques. La qualité du terrain est fonction à la fois de la position du point de terrain visé et de la position de l'avion dans le terrain ; en effet selon la position de l'avion dans le terrain tous les points du terrain ne sont pas forcément vus à un instant donné par le radar (phénomènes de masquage). Il est donc très difficile de valider ce mode compte tenu de la combinatoire des cas envisageables.

Dans le cas de l'utilisation du radar, on est donc en présence d'un système bouclé où la trajectoire dépend du terrain et inversement.

Le fait que le pilote puisse de plus avoir le choix entre un pilotage manuel (trajectoire suivie choisie par le pilote) et un pilotage automatique (trajectoire suivie calculée par le système) augmente encore le nombre de degrés de liberté du système.

Enfin, la notion de sécurité est essentielle en suivi de terrain. Du fait de la hauteur de vol visée, le droit à l'erreur est très limité. Il est donc important de pouvoir maîtriser les conséquences des pannes dans la performance de la fonction.

Il apparaît donc que la définition d'une fonction "suivi de terrain" est d'une réalisation ardue pour laquelle l'utilisation de simulations "temps-réel" interactives semble apporter un moyen complémentaire de contrôle et d'analyse tout à fait approprié et nécessaire à la bonne définition du mode.

5. DESCRIPTION DE LA SIMULATION SUIVI DE TERRAIN

La simulation "temps-réel" interactive de la fonction suivi de terrain respecte la définition générale des simulations radar.

Elle est constituée :

- des différents modèles
  . un modèle radar
  . un modèle de trajectoire 3D
  . un modèle avion
  . un modèle d'asservissement à la trajectoire
  . un modèle de terrain
  . des modèles d'environnement
- de bases de données
  . une base de données de terrain numérisé
  . une base de données graphique du terrain
- un poste de commande radar
- un poste de commande de la simulation avec :
  . sélection des paramètres de simulation
    - hauteur minimale de vol
    - dureté de la trajectoire
    - trajectoire horizontale
    - suivi de terrain automatique/manuel
    - début, arrêt, pause, ...
    - ...
  . sélection des visualisations
    - visualisations radar
    - visualisations de servitude
    - options pour chaque visualisation
  . sélection des paramètres radar
    - secteur exploré
    - paramètres de la carte
    - ...
- des visualisations radar
  . visualisations 3D
    - Type "tête haute" - visualisation du terrain 3D en perspective conforme au terrain extérieur et en projection sur celui-ci dans la limite du champ du viseur + visualisation de la trajectoire 3D et des paramètres avion
    - type "tête basse" - visualisation du terrain 3D en perspectives non conforme sur la totalité du champ exploré et sans visualisation du terrain extérieur
  . visualisation 2D
    - visualisation du terrain "vue de dessus" avec codage des couleurs en fonction soit de l'altitude absolue soit de l'altitude rérérencée par rapport à l'altitude avion avec positionnement d'une maquette avion
  . visualisation 1D
    - visualisation du profil de terrain suivi, de la maquette avion dans ce terrain et de la trajectoire verticale
- une gestion de la simulation permettant d'activer le modèle radar et d'un restituer les performances à une cadence conforme à la réalité.

6. INTERET DE LA SIMULATION "SUIVI DE TERRAIN"

Nous avons vu précédemment l'intérêt des simulations "temps-réel" interactives dans les systèmes radar de pointe avant. Le but de ce paragraphe est de montrer comment cela s'applique plus particulièrement à la simulation "suivi de terrain".

- Démonstration

La simulation peut être utilisée comme outil de promotion en démontrant le bon comportement du radar dans cette fonction. Cette simulation permet de montrer l'aptitude du radar à délivrer les paramètres de terrain avec un bon niveau de performance et prouve un savoir-faire de l'industriel dans le développement de cette fonction. En effet, tout utilisateur de la simulation peut en prouver la robustesse en effectuant des survols de terrain à l'altitude souhaitée, en choisissant lui-même les différents paramètres de la simulation et les trajectoires suivies (notamment en pilotage manuel) et de ce fait préjuger du bon comportement du radar dans sa fonction suivi de terrain.

- Validation de concept

La simulation sert également à la validation de concept. Elle permet de valider l'architecture générale de la fonction et d'entériner les choix de la définition du radar, tant au niveau de la forme d'onde et des traitements associés que de la gestion interne ; ces choix étant issus de l'expérience, des études théoriques et des simulations numériques fines. La simulation temps-réel interactive vient donc en complémentarité de ces moyens, en donnant accès à un grand nombre de scénarios qu'il n'est pas toujours facile de mettre en œuvre dans le cas de simulations classiques, pour lesquelles l'absence d'interactivité "temps-réel" ne permet pas de réagir à une situation nouvelle découverte lors d'un vol simulé.

Elle sert également à valider les principes retenus pour l'élaboration des trajectoires 3D. En effet les principes retenus dans les différents cas de pilotage (automatique ou manuel) ou les effets de la prise en compte du renouvellement du terrain dans l'élaboration de la trajectoire ne peuvent être définitivement validés que dans une simulation temps-réel qui est le seul moyen de se rendre compte de la nature des mouvements générés pour l'avion.

Dans le cas de la polyvalence élargie, cette simulation permet de montrer l'utilisation d'une fonction Air-Air simultanément à une fonction suivi de terrain.

- Prédimensionnement de système

La simulation est utilisée lors du prédimensionnement du système pour la détermination des paramètres de la carte (dimensions, maille, résolution, précisions, cadence de renouvellement, ...) nécessaires à l'élaboration d'une trajectoire optimale.

- Aide à l'étude de la fonction suivi de terrain

Dans la phase d'étude, la simulation permet d'affiner les traitements, de se conforter dans leur choix et de mettre au point les principes de gestion. Il s'agit par exemple de la définition du secteur angulaire exploré, de la gestion de cette exploration, de la gestion de la carte et de la validation de la robustesse des traitements envisagés sur la plus grande combinatoire possible de types de terrain, de trajectoires et de conditions extérieures.
Dans le cas de la mise au point de la sécurité elle permet d'envisager les conséquences des pannes en modélisant leurs effets dans les traitements radar bien mieux que dans un système réel car ces pannes sont déclenchables à volonté et dans n'importe quelle situation alors que dans le matériel la probabilité d'occurence de ces pannes est très faible.

- Aide à la définition de l'interface homme-système

La simulation temps-réel interactive de par sa conception est l'outil de base dans la définition de l'interface homme-système, puisque représentative des commandes et des visualisations. La simulation permet, en premier lieu et à partir d'une prédéfinition provenant de la réflexion d'ingénieurs et d'opérationnels, de réaliser une maquette préfigurant l'état final. Cette maquette est ensuite soumise à l'analyse critique de toutes les parties concernées pour évoluer vers un état représentatif de la définition de l'interface homme-système du radar.

- Aide aux essais en vol

La simulation est une aide à la définition des essais en vol, en pré-jouant les essais avant leur déroulement réel. Elle permet de mettre en évidence les particularités du vol. En suivi de terrain, elle permet de montrer le terrain radar tel qu'il doit être restitué par celui-ci, de mettre en évidence les points particuliers et de familiariser l'expérimentateur à la trajectoire suivie. Elle permet de préparer les scénarios des essais (itinéraires, mise en place de brouilleurs, ...).

- Extrapolation des essais

A l'issue de la phase d'essais, la simulation est "recalée" de la connaissance supplémentaire par comparaison des résultats des essais avec les résultats prédictifs obtenus avec le modèle. Les essais en suivi de terrain n'étant autorisés qu'au-dessus de régions bien déterminées en général peu habitées, il est intéressant de présager de ce que serait cette fonction suivi de terrain dans les endroits non autorisés. La simulation permet alors d'extrapoler les résultats obtenus lors des essais en vol. Elles permet également de superposer à des vols simulés, représentatifs du fonctionnement réel, des phénomènes réels découverts lors des essais en vol ou des pannes simulées.

- Intégration système

L'utilisation de modèles radar permet de préparer l'intégration système par la validation de la bonne prise en compte des entrées-sorties en vérifiant notamment les protocoles d'échange par un balayage exhaustif des données du modèle et plus particulièrement des alarmes générées.

- Dialogue utilisateur

La simulation permet de familiariser l'utilisateur avec les différentes commandes d'utilisation du radar, dans l'interprétation des visualisations et dans les transitions de comportement lors d'arrivée d'événements extérieurs ou de pannes en l'entraînant aux modes dégradés.

7. CONCLUSION

Dans cet article, il a été montré l'apport des simulations temps-réel interactives dans le développement des systèmes radar et plus particulièrement dans sa fonction suivi de terrain.

Cette fonction est particulièrement difficile à mettre au point car en plus des performances requises, elle nécessite un haut niveau de sécurité. De plus, le domaine d'utilisation de cette fonction est très vaste - tous types de terrain, tous types d'environnement, ... - ce qui en fait une fonction très complexe à développer

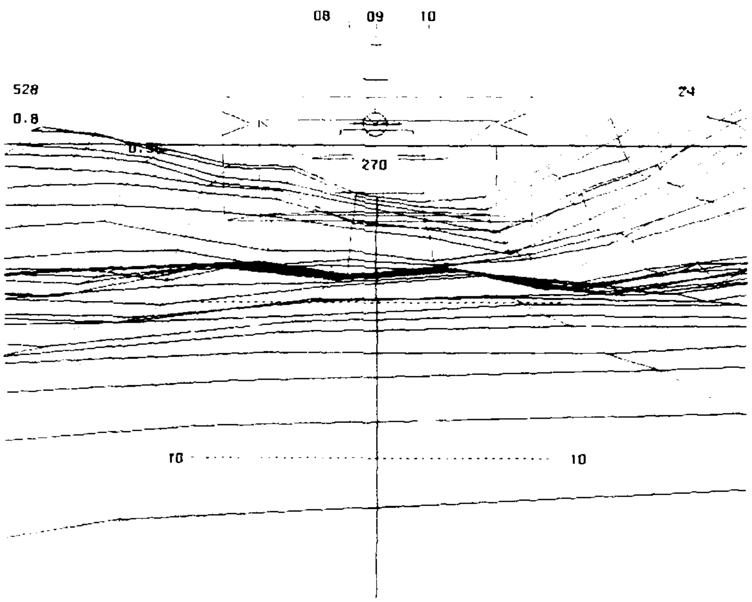
qui nécessite l'emploi des outils les plus sophistiqués.

La simulation temps-réel interactive, qui vient en complémentarité des autres moyens existants, intervient à tous les stades de développement du radar.

Elle permet de montrer la fonction telle qu'elle est envisagée, de valider les concepts mis en œuvre, de prédimensionner le système, de venir en complément des études notamment au niveau de la gestion, de définir et d'extrapoler les essais en vol en enfin de préparer le futur utilisateur à son emploi.

La simulation temps-réel interactive suivi de terrain est donc un outil tout à fait approprié et nécessaire au développement de la fonction suivi de terrain.

VISUALISATION S D T



USE OF HIGH-FIDELITY SIMULATION IN THE DEVELOPMENT OF AN F/A-18 ACTIVE GROUND COLLISION AVOIDANCE SYSTEM

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Summary

An active Ground Collision Avoidance System (GCAS) has been developed for the F/A-18 using the Naval Air Test Center's F/A-18 simulation. The simulation has been used for the development of all three components of GCAS: (1) the algorithms used to determine the recovery initiation altitude; (2) the additional flight control laws (FCL's) necessary to perform the recovery maneuver; and (3) the visual and audio cues used to provide recovery status information to the pilot. The use of a simulation has allowed the rapid development of a viable F/A-18 GCAS that incorporates technology from the F/A-18 Integrated Fire and Flight Control (IFFC) simulation and the Advanced Fighter Technology Integration (AFTI) F-16 program. Complete system development and preliminary evaluations were performed using the simulation. This increased overall project safety while decreasing development and potential flight test costs significantly.

Introduction

In the United States Navy alone, as many as nine aircraft were lost as a result of controlled flight into terrain (CFIT) during 1988. The pilots became distracted, saturated by their workload, incapacitated, or simply "flew into the ground", resulting in the loss of lives and millions of dollars of hardware. Clearly, with the advanced control systems of today's aircraft, these losses are not only tragic but unnecessary.

Flight tests conducted with the AFTI F-16[1] have shown that an increase in safety could be realized with the use of an active GCAS rather than the existing passive systems. Developed mainly as a fail-safe against pilot loss of situational awareness and g-induced loss of consciousness (GLOC), the Navy saw the potential application toward its own tactical aircraft, in particular the F/A-18, which has more than twice the incidence of GLOC per 10,000 flight hours (12.9) than any other aircraft in the Navy inventory[2]. With its digital flight control system, the F/A-18 is extremely adaptable to new control technologies, and the decision to fund a proof-of-concept active F/A-18 GCAS was made during fiscal year 1990. Furthermore, development of this active GCAS and its subsequent evaluations against the F/A-18's current low altitude warning system would be done exclusively using a simulator.

The Manned Flight Simulator (MFS) facility located at the Naval Air Test Center (NATC) has developed a high-fidelity, non-linear, real-time F/A-18 engineering simulation. The simulation has been used in support of numerous Navy flight test projects, investigations of various Navy fleet incidents, and the National Aeronautics and Space Administration High Angle-of-attack Research Vehicle program. The facility includes an actual F/A-18A cockpit; a 40 foot (12 meter), 360° field-of-view dome; a six-degree-of-freedom motion platform; and a CompuScene IV image generation system.

This paper shall address the advantages of using simulation to develop and evaluate an active GCAS, and present results, recommendations, and lessons learned.

GCAS Design Philosophy

An overview of the GCAS implementation is shown in Figure 1. The additional FCL's are external to the flight control computers (FCC's), and the GCAS recovery commands are summed into the longitudinal and lateral axis stick command paths of the existing FCL's. The FCC would use the summed GCAS and pilot commands in the same way it currently uses only the pilot command. The GCAS control loop is closed by feedback of measured aircraft responses provided by current aircraft sensors; no additional instrumentation would therefore be necessary. GCAS is active only when the aircraft altitude is at or descending below the computed recovery initiation altitude; it remains active until the aircraft achieves a positive 5° flight path angle. This angle was chosen to provide a positive rate of climb after pull-up at nominal pitch attitudes throughout the flight envelope while maintaining a sufficient energy state.

An auto-recovery system must perform two distinct tasks: (1) decide when a recovery maneuver must be initiated in order to pull out at or above the pilot-designated floor altitude; and (2) supply control system commands to perform the maneuver. The design philosophies for each of these tasks, along with the recovery system cuing, follow.

Recovery Altitude Calculations

The algorithms of the Straight-Forward Auto-Recovery System (SFARS)[3] were found to be best suited for the GCAS recovery altitude computations. The simulation was used to determine the aircraft-specific gain schedules used in these algorithms. The SFARS algorithm determines the altitude that will be lost during a given recovery maneuver (Δz). This is then added to the pre-selected floor altitude to obtain the recovery initiation altitude. The original algorithm used six independent components that compensated for dive angle, bank angle, g-onset, sensor lag, excess (i.e. non-idle) power, and roll rate at recovery initiation.

Initially, two of the six components were neglected from the system build-up: sensor lag and roll rate at recovery initiation. Potentially, the most crucial sensor lag would be that of the mean sea level (MSL) altitude sensor; the above ground level (AGL) sensor is not used at this time because of its limited coverage in some aircraft attitudes. Based on AFTI flight test results[3], the MSL sensor was found to have little or no time lag so this compensation term could be neglected. The roll rate compensation term was neglected since this system is designed for recovery from CFIT situations and these situations typically have low roll rates. In the future, if this system is expanded for use in other situations, the roll rate term may become important. Later, the excess power compensation was also excluded in favor of using the F/A-18's Automatic Throttle Control (ATC) system, as will be discussed later.

The derivations of the original SFARS equations can be found in References 1 and 3. The final form of the F/A-18 derivative system is shown, in block diagram form, by Figure 2.

The gain schedules for dive angle and g-onset compensation were determined first, followed by the bank angle and excess power compensation terms. The entire system was optimized for the fighter escort (FE) configuration, an air-to-air store loading.

The dive angle compensation term is computed using the following:

$$\Delta z_1 = \frac{V_{true}^2 (1 - \cos\gamma)}{K_1 g}$$

where V_{true} is true airspeed (ft/sec), γ is the flight path angle (radians), and g is the acceleration due to gravity (ft/sec^2). K_1 was initially defined as a function of calibrated airspeed only. The gain schedule was developed using the simulation to gather recovery data at various airspeeds during a 30° dive. The schedule was optimized so that recoveries at all airspeeds fell within the acceptable recovery window of 200 feet (61 meters) above the floor altitude. After subsequent problems with steeper dive angle recoveries penetrating the floor altitude, the schedule was modified to include flight path angle in the schedule's functionality, as shown by Figure 3.

The bank angle compensation term is computed from the following equation:

$$\Delta z_2 = \frac{|\phi|}{K_2} |V_D| + (|\phi| - 45) K_\phi$$

where ϕ is the bank angle (deg), V_D is the inertial frame downward velocity (ft/sec), and K_2 is essentially the roll time constant which is scheduled with calibrated airspeed. This schedule is shown in Figure 4 and was also optimized using the simulation to gather data at various speeds and 30° of bank angle in concert with the previously optimized dive angle compensation. The K_ϕ portion of the Δz_2 equation was added after it was determined that the commanded roll rate is not only a function of airspeed, but also the bank angle of the aircraft. The GCAS control laws will command different roll rates depending on the bank angle. Using the excess power compensation term of the original SFARS algorithm as a guide[3], this empirical fit was developed with an intercept of ϕ = 45° and a slope (K_ϕ) of 1.3 ft/deg (0.4 m/deg). The K_ϕ portion of this term is retained only if it is positive.

The g-onset compensation term is determined by the amount of time it takes to reach a desired load factor. The equation for the altitude lost during this process is simply:

$$\Delta z_3 = K_3 |V_D|$$

The value of the K_3 gain is the aircraft's g-onset time constant. The first value used, 1.1 seconds, was that of the AFTI F-16, found in Reference 3. This value turned out to be close enough to the F/A-18's actual time constant of 1.2 seconds that no changes were warranted.

The excess power compensation term was initially included to handle non-idle power situations. Its equation was:

$$\Delta z_5 = \frac{V_{cal} a_z - K_{p_s}}{K_5}$$

where K_5 = 11.85 scaling coefficient
K_{p_s} = 9,300 knots-ft/sec^2 (2,834 knots-m/sec^2)

V_{cal} is calibrated airspeed (knots). The value of K_{p_s} is defined as the flight condition where specific excess energy (p_s) is zero at a normal acceleration (a_z) of 128.8 ft/sec^2 (39.24 m/sec^2) or 4 g's, and was obtained from F/A-18 maneuvering diagrams. While this compensation term worked adequately for the more shallow dive angles ($\gamma \leq$ 30°), it was found to be less accurate at compensating for the elevated energy levels and accelerations associated with steeper dives. Problems with this term were confirmed through conversations with the author of Reference 1. It was suggested that aircraft equipped with an automatic throttle system may be better served by tying into it rather than compensating for altitude loss in the recovery algorithms. As a result of this suggestion, the F/A-18 GCAS was modified to engage the aircraft's ATC five seconds prior to pull-up in order to allow the engines sufficient time to spool down to idle. Upon selection by GCAS, the ATC drives the throttles to flight idle for the duration of the recovery maneuver. After recovery is completed or if a manual disengagement is commanded, the ATC restores the throttles to their original position. This approach required only minor changes to the ATC control laws to allow engagements outside of the normal authority of the system when GCAS is active.

Flight Control Law Modifications

The additional FCL's necessary for the aircraft to perform the auto-recovery maneuver are shown in detail by Figure 5. These FCL's descended from the early General Electric FIREFLY routines via an F/A-18 IFFC simulation developed by NATC. Gain schedules for the longitudinal axis FCL's were optimized through the course of several simulation runs at a constant dive angle and various airspeeds to obtain acceptable aircraft responses across the flight envelope to GCAS commands. Both longitudinal and lateral axis systems are simple proportional command

systems. Open-loop analysis of this system yielded no safety of flight or stability concerns, however, a closed-loop analysis should be completed before any flight testing begins.

Pilot-Vehicle Interfaces

Pilot-vehicle interfaces with GCAS are kept as simple as possible. The desired floor altitude is pre-selected prior to the simulation run and entered into the system. During real-time runs, the pilot is required to enable the system via a cockpit switch selection. While active, the system is disabled whenever the landing gear is extended, the flight control system (FCS) enters spin recovery mode, or a momentary selection of the control column paddle switch is made by the pilot. The system automatically re-activates upon landing gear retraction or resumption of normal FCS operation in conjunction with a positive climb attitude above the designated floor altitude.

Recovery System Cues to the Pilot

The major recovery system visual cue consists of a pair of chevrons presented on the head-up display (HUD) approximately five seconds prior to initiation of the automatic recovery. As the aircraft continues its descent, the chevrons draw together to form a break "X" at the pull-up altitude (Figure 6). This symbology, chosen because of its simplicity and intrinsic meaning to a tactical pilot, is identical to that used in the AFTI F-16 GCAS flight test aircraft[1]. If the pilot intervenes before the pull-up point by moving the stick in such a way as to delay the onset of the pull-up point (e.g. decreasing the dive angle), the chevrons will begin to part again, indicating that the actual pull-up point is being revised by GCAS. Also, the rate at which the chevrons come together indicates how quickly the aircraft is approaching the pull-up point. The HUD symbology (including the chevrons) was programmed onto a graphics processor and projected ahead of the pilot. The normal HUD "ATC" cue is also provided whenever GCAS engages the automatic throttle control system during a recovery.

An audio voice alert ("ALTITUDE...ALTITUDE"), identical to that already installed in the F/A-18, is provided to the pilot whenever the aircraft penetrates the floor altitude.

Aim and Methodology of Piloted Evaluations

Although the original tasking was to compare the active system against the F/A-18's current low altitude warning system, it was decided that such a comparison would be moot. The current system in the F/A-18 provides only a voice alert *at* the pre-selected floor altitude, ensuring floor penetrations in every case. Thus, piloted evaluations of GCAS were approached from slightly different aspects: (1) to evaluate the automatic recovery system performance, from a *qualitative as well as quantitative standpoint*; and (2) to qualitatively evaluate manual recoveries performed by the pilots using the cues provided by GCAS. This information could be used to assess the value of GCAS in a passive mode, as well as to determine the most effective cue(s) to use with a passive GCAS.

Targeted test points for evaluation of the active GCAS comprised a matrix of three airspeeds (300, 375, and 450 KCAS), three dive angles (30°, 45°, and 60°), three power settings (idle, military, and maximum afterburner), and five bank angles (0°, 30°, 45°, 90°, and 180°). Table I shows the nine points targeted during the passive GCAS evaluations.

V_{target} KCAS	γ deg	ϕ deg
300	30	30
375	30	45
450	30	0
300	45	0
375	45	45
450	45	180
300	60	30
375	60	0
450	60	45

Table I

Two different store loadings, both in the up/away (i.e. cruise) configuration, were tested: (1) FE at 36,124 lb (16,385 kg) and 22.1% cg as tested; and (2) interdiction (INT), an air-to-ground loading at 46,284 lb (20,994 kg) and 20.93% cg as tested. Figure 7 illustrates both of these loadings. The INT loading was tested to identify any important configuration-dependent parameters that may exist, which will be useful in the event separate gains based on store loading must be optimized. Each configuration was flown by at least two different test pilots, with a total of four pilots participating in the evaluations.

During the automatic recovery phase, the pilots were asked to set up the required test points, note the critical parameters (i.e. airspeed at pull-up, minimum altitude during recovery, and peak load factor), and provide qualitative assessments of the system performance.

For the evaluation of the manual recoveries, the pilots were not briefed on which points they would see. Additionally, the simulation's visual system was set up to present a cloud base at 3,500 feet (1,067 meters) MSL such that the pilot would have no visual scene references above that cloud level. Together, these helped to induce a loss of situational awareness to the pilot that would not have been otherwise present had he flown the aircraft into the dive/bank angle condition himself. The pilot was required to look away from cockpit instrumentation while the simulation was set up above the cloud base already in the dive/bank condition desired for the test point. After the simulation run had begun, the pilot was then required to make an assessment of his aircraft's attitude and determine if any immediate action was required. If not, the dive would be allowed to continue until pull-up cues were provided by GCAS, at which point, the pilot would be required to perform the recovery maneuver. For the manual recoveries, the HUD chevrons were identical to those used during the automatic recovery sessions, but the voice alert was provided at the pull-up point rather than at floor altitude penetration. Two manual recovery cuing schemes were evaluated: (1) the voice alert cue only; and (2) both the break "X" and voice alert cues.

Discussion of Results

Figures 8 through 10 present results from the piloted evaluations of the active GCAS in the FE configuration. Figures 11 through 13 contain the results for the INT configuration.

Generally, the FE results were within the design tolerance of 200 feet (61 meters) above the floor altitude. At the lowest airspeed tested (300 KCAS), the system had no penetrations and only one point was out of tolerance. There was a marked increase in the scatter at higher airspeeds and steeper dive angles. It is likely this is due to the many acceleration profiles that can lead into and out of the pull-up point. The calculation of the dive angle compensation term, Δz_1, assumes a constant velocity and therefore a circular trajectory throughout the recovery. Different acceleration profiles will cause scatter in the average velocities of the recovery maneuvers and a corresponding scatter in the recovery altitudes. At higher airspeeds and dive angles, there is a larger range of acceleration profiles, and therefore, wider altitude scatter.

Overall, the INT cases showed only a shift to a more conservative recovery with increasing dive angle, but there were a significant number of floor penetrations at the lowest airspeed tested (300 KCAS). Associated with each recovery at this condition was an angle of attack of 20° to 25° and a normal acceleration of under 4 g's, indicating near stall conditions for that gross weight. This also caused an uncomfortably high post-recovery nose attitude ($25° \le \theta \le 30°$), since the system's aim is to bring the aircraft's flight path to a positive 5° attitude. Additionally, the peak angle of attack values achieved during these recoveries exceeded the Naval Air Training and Operating Procedures Standardization (NATOPS) angle of attack limit of 20° for this store configuration. INT results improved significantly at higher airspeeds without exceeding NATOPS maneuvering limits; however, there were still several floor penetrations at the inverted bank angles. This is possibly due to roll rate limiting imposed by the FCL's with this store loading.

Pilot reactions to the system overall were positive. The majority felt comfortable enough with the system to trust it in situations of GLOC and spatial disorientation, as well as operationally in the navigation mode, air-to-air arena, and some limited air-to-ground instances (e.g. training).

A cursory look at two asymmetric store loadings and their effect on active GCAS recoveries was done at the end of the evaluations. The smaller lateral asymmetry, 3,800 ft-lb (5,152 N-m), was achieved by removing one of the wingtip AIM-9 missiles from the FE loading; removal of two of the MK83 bombs from one of the outboard wing stations of the INT loading provided the larger lateral asymmetry of 22,000 ft-lb (29,828 N-m). GCAS was able to effectively recover the aircraft to a wings level climb condition with the smaller lateral asymmetry, however, with the larger one, the system could not achieve a complete recovery. The nose attitude was brought up to level, but the large asymmetry continued to drop the heavy wing during the recovery maneuver, resulting in a "porpoising" motion as one recovery after another was attempted by GCAS.

Use of the F/A-18's ATC for handling elevated power conditions gave far fewer floor penetrations than did use of the original SFARS power compensation term. None of the pilots found use of the system objectionable, however, several commented on the timing and amount of automated power application after recovery. The unanimous suggestion on power application was that the system should select military as the nose passes through the horizon during the recovery. One pilot pointed out that the current ATC system may be inadequate for GCAS use due to system reliability issues or the simple fact that pilot selected throttle friction may prevent the system from engaging, as the throttles must move during ATC operation.

The HUD chevron mechanization was immediately accepted by the pilots. All agreed that the chevrons provided several necessary cues on pending system engagement that could be absorbed through their peripheral view. For instance, the rate of closure provided an easily perceptible cue on the sense of urgency of the situation. Slowing of the closure rate or chevron separation provided useful feedback on if and how well the pilot was affecting the situation when he chose to intervene.

Aural cuing as it applied to both active and passive recoveries was viewed as necessary by the pilots. For the active recovery cases, the pilots preferred to have as many cues as possible to notify them that the system was taking control. During the manual recoveries, many pointed out that often times, pilots are not concentrating on the HUD, but are scanning about their aircraft. In such instances, the aural cue serves to notify them of something requiring action and brings their attention back into the cockpit. All agreed that the aural cue should not be used alone, but in conjunction with other cues (e.g. the HUD chevrons).

Due to the limitations of current simulation technology, no direct comparisons can be made between the active and passive GCAS results. While considerations to visual and tactile cues need not be made with respect to the active GCAS, pilots rely heavily upon these cues to perform maneuvers such as a constant g pull-up to wings level.

Overall, there is no life-threatening condition in a simulator, and the pilots realize this, at least on a subconscious level. Poor resolution and lack of depth perception inherent in domed visual systems makes it difficult for the pilot to evaluate the aircraft's situation and the necessity for action in an unknown dive condition. Also, once a recovery maneuver is in progress, the lack of acceleration cues makes a realistic manual pull-up difficult in a simulator. In general, however, recoveries made by GCAS were more consistently above the floor altitude than were the manual recoveries. It was also observed that the pilots often, either intentionally or inadvertently, pulled more than the system-targeted 4 to 5 g's during the manual FE recoveries. Many times, this had the effect of compensating for the lag associated with human response to provide recoveries above the floor altitude, some even quite conservative. These normal acceleration overshoots occurred more when the only recovery system cue provided was the voice alert. This was not the case with INT manual recoveries due to the fact that both the active GCAS and the pilots tended to load the aircraft up to the normal acceleration limit enforced by the FCC's. In regards to the issue of cuing for manual recoveries, all the pilots agreed

that the chevron and voice alert combination was superior to the voice alert only. Results generally supported this, as recoveries were typically better when the chevrons were used as compared to the same conditions using audio only, although there was a large amount of scatter.

Conclusions

The usefulness of simulation has been demonstrated in the development of an active GCAS for the F/A-18. Control system gains as well as the recovery system itself were developed in a timely manner at minimal costs.

The shortcomings of a fixed-based simulator manifested themselves in the testing of the passive GCAS, where the results were clouded by the fact that the visual scene in the dome was not sharply defined and provided no depth perception, and there was no tactile cuing.

In its current form, the active GCAS has demonstrated the potential for reducing aircraft losses due to cases of GLOC or spatial disorientation. Nuisance warnings and nuisance pull-ups have been kept to a minimum. In the operational air-to-air and basic navigational modes, the system is adequate as is, but can be refined further. For air-to-ground, GCAS is currently adequate only for training use. Operationally, it is currently inadequate for the air-to-ground mission, but can be made acceptable with work.

Active GCAS appears to perform a given recovery maneuver more efficiently than a pilot could, with fewer floor penetrations. Passive GCAS is inferior to active GCAS, particularly in instances of GLOC or spatial disorientation, but appears to have its place in other applications. In either case, GCAS is more effective at preventing floor altitude penetrations than the low altitude warning system currently in place on production F/A-18's.

The more cues provided to the pilots about impending trouble and/or active GCAS engagement, the better. The HUD chevron/break "X" mechanization, as implemented for this study, is highly desirable. Voice alerts are also desirable but should only be used to complement the chevrons.

If available and reliable, an automatic throttle system used in conjunction with an active GCAS provides a simpler and more effective method of compensating for elevated power conditions during automatic recoveries.

AGL sensors must be used in the long-term for GCAS to have value over all terrain features with as little pilot intervention as possible.

A GCAS system, whether active or passive, is necessary for military tactical aircraft. The SFARS algorithms developed by the United States Air Force have given the United States Department of Defense a viable and inexpensive system, that due to its generic nature, is easily adaptable for use in all its tactical aircraft. The simulation work presented in this paper has provided the United States Navy an SFARS-derivative system that appears to work on the F/A-18.

Recommendations

Continue simulation work in order to refine the role GCAS will play in the air-to-air and air-to-ground arenas. Investigations into optimum default settings of floor altitudes for each and the merit of passive GCAS in the air-to-ground mission can be made. The take-off and powered approach phases of flight must also be considered with respect to GCAS. Passive GCAS may initially be the best solution, but the feasibility of active GCAS in these flight regimes may also be explored.

Investigate solutions to GCAS problems observed during engineering and piloted evaluations in stalled and near-stalled portions of the flight envelope. One possible answer may be for GCAS to add enough power to sufficiently elevate the aircraft's energy state prior to recovery initiation in order to avoid a dynamic or deep-stall condition.

Use simulation to correct the current inability of the active GCAS to effectively handle large asymmetric store loadings.

Develop a method to predict the average velocity of the recovery for use in the calculation of the dive angle compensation term. This term should reduce the amount of scatter in the recoveries due to the different acceleration profiles.

The roll time constant gain, K_2, should be varied with store loading in order to compensate for reduced roll rates resulting from FCL limiting with heavy store loadings.

Use simulation to investigate the effect of insidious INS failures and INS dumps on GCAS performance. Simulation is ideally suited to explore the repercussions of such failures and help point the way toward any necessary GCAS failure modes. Additionally, simulation may be used to safely evaluate the effects of degraded FCS modes on GCAS performance.

Use simulation to explore various switching and blending schemes between MSL and AGL sensors in order to compensate for the current failings in radar altimeter coverage.

Expedite installation of 360°-coverage radar altimeters onto production tactical aircraft.

Using the simulation, implement and evaluate the changes recommended by the pilots concerning the timing and amount of power applied by GCAS during recoveries. A long-term solution to the issues of ATC reliability and engagement ability could be the use of a digital engine controller.

Present the break "X" cue on all cockpit displays, so that the pilot may receive the necessary cuing in instances where he is watching a forward-looking infrared or strike camera image on a digital display indicator rather than the HUD.

Use of the MFS motion platform and its virtual image mirror may allow more accurate evaluation of passive GCAS.

Perform a closed-loop analysis on the GCAS FCL's. This must be done prior to flight testing.

Implement the v1.1 GCAS in an F/A-18 technology demonstration airplane for flight testing. This may be done prior to completion of much of the previously recommended simulation work.

Finally, expedite installation of GCAS into production F/A-18 aircraft.

Acknowledgments

The authors would like to express their gratitude to members of the Simulation and Control Technology Department of the Strike Aircraft Test Directorate, and the Computer Technology and Simulation Department of the Systems Engineering Test Directorate for their contributions to this project. The authors would specifically like to thank Mark Hendrix and Michael Colony, who laid the initial groundwork for the F/A-18 GCAS algorithms presented in this paper; William McNamara and Cynthia Wathen, who provided engineering support for this effort; and the test pilots who participated in the evaluations: LtCOL Troy Pennington, USMC; LCDR James Galanie, USN; CAPT Christopher Hadfield, CAF; and LT David Prater, USN.

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GCAS Implementation Schematic

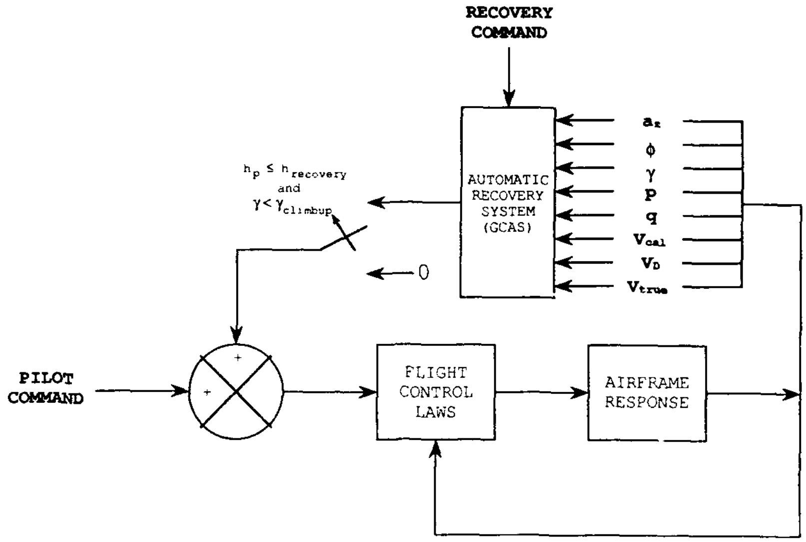


Figure 1

F/A-18 SFARS Implementation

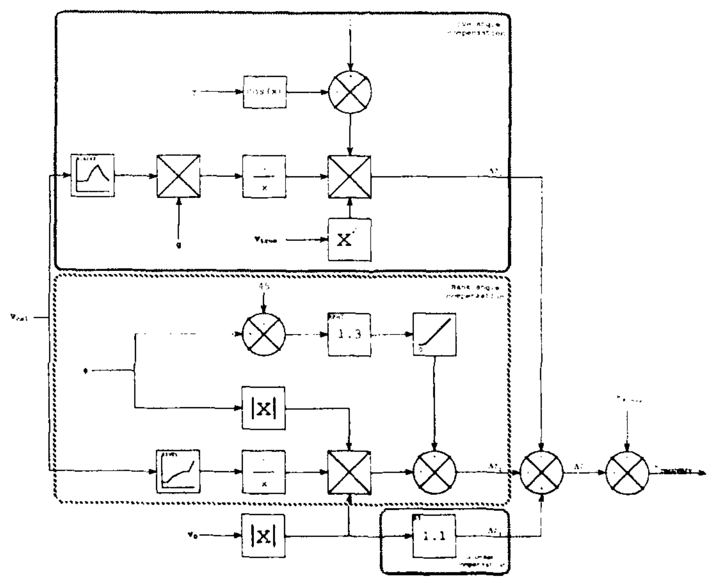


Figure 2

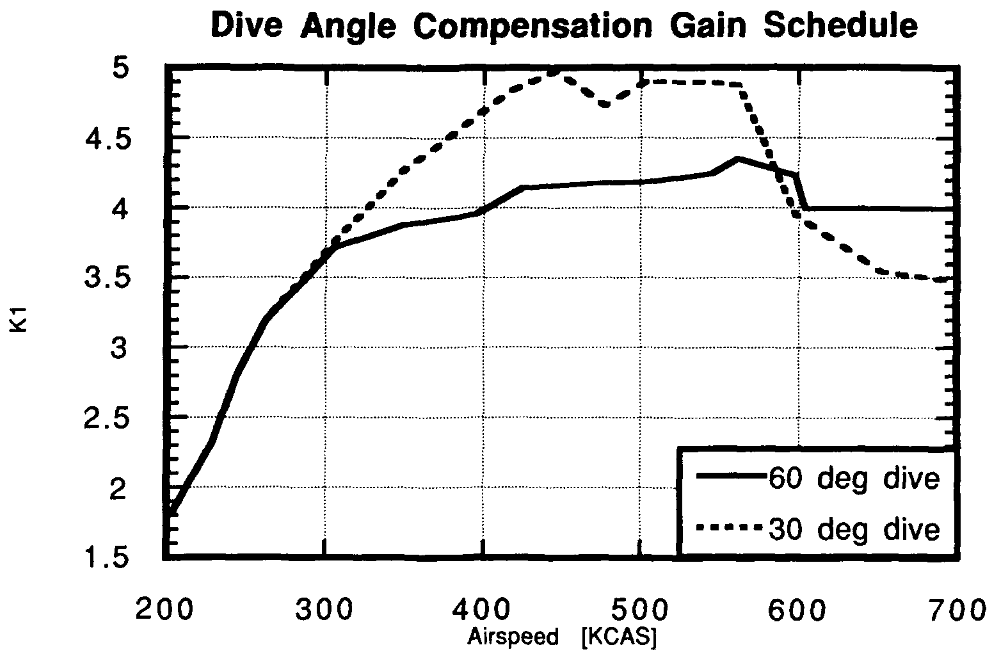


Figure 3

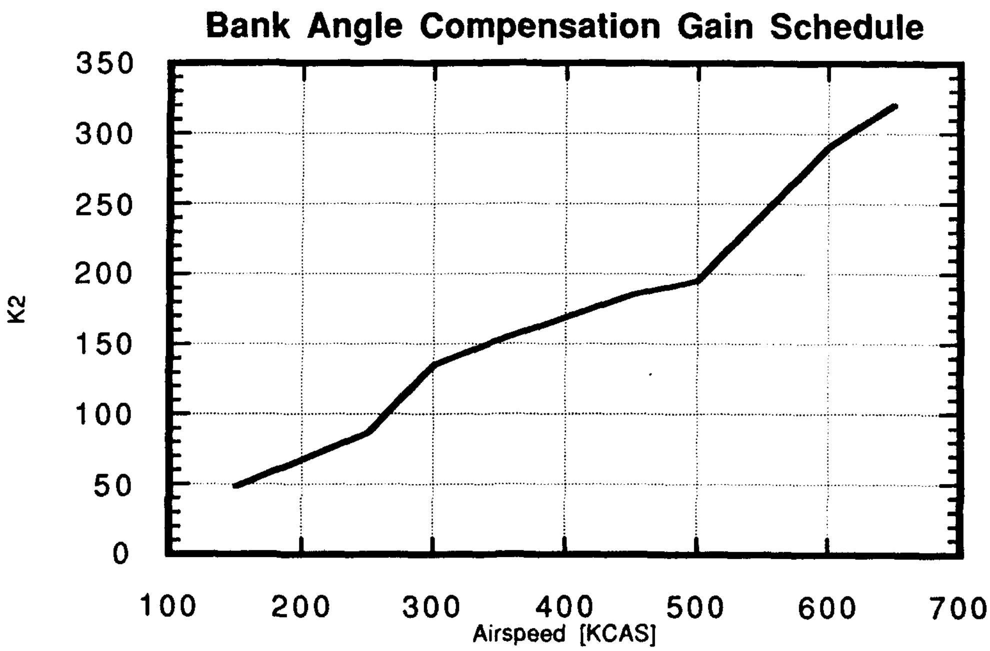


Figure 4

F/A-18 GCAS Control Law Additions

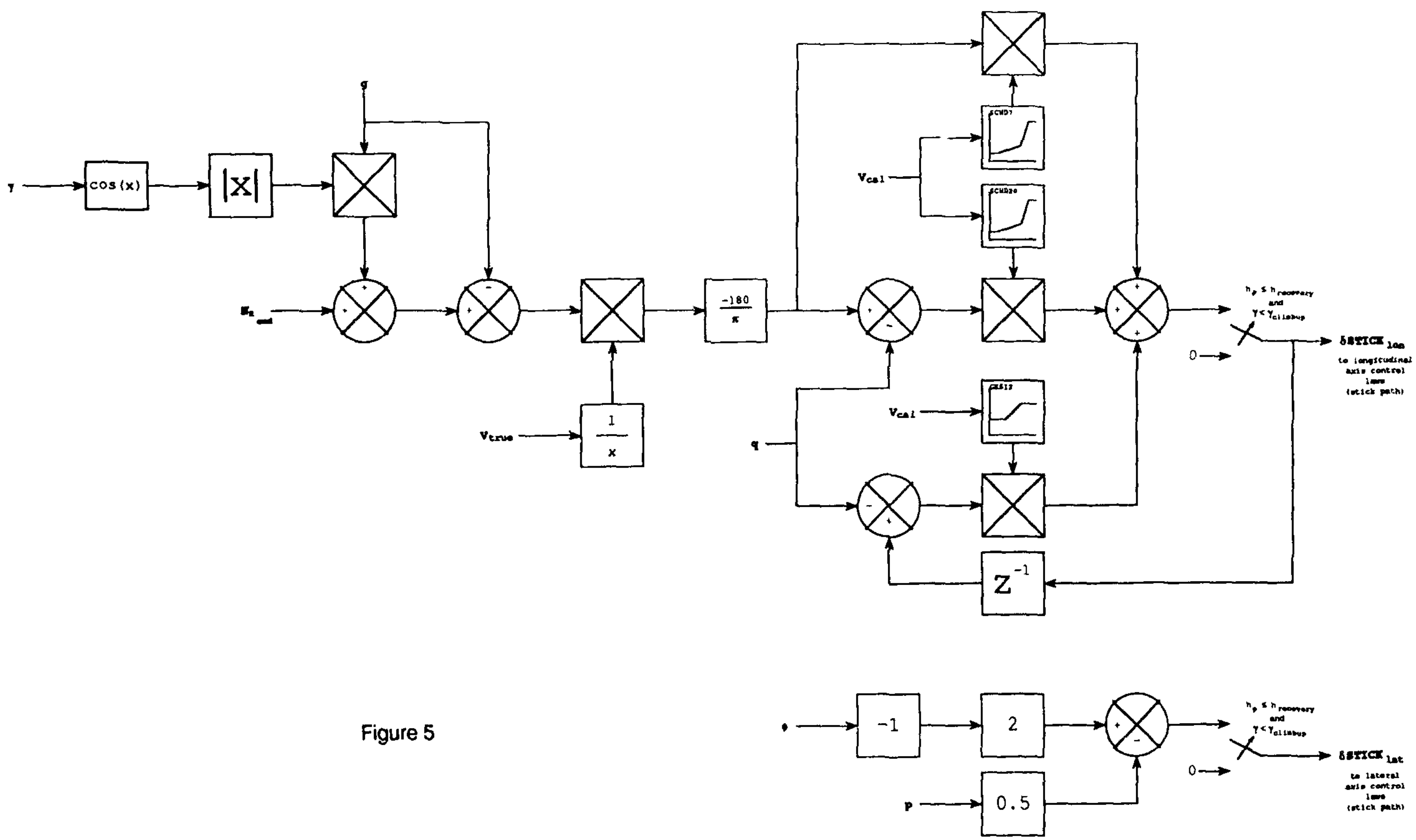
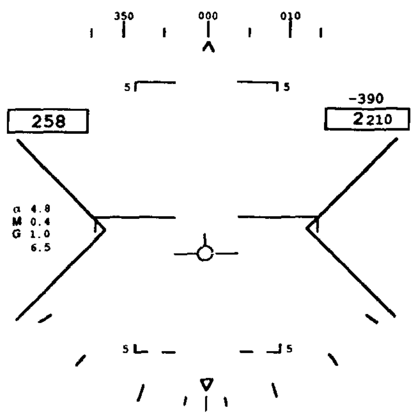
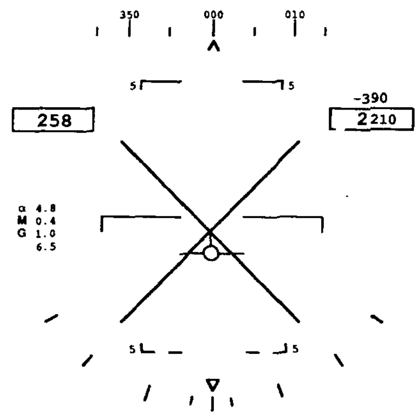


Figure 5

F/A-18 GCAS HUD Symbology



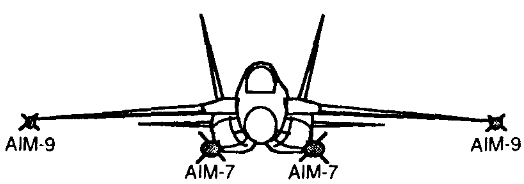
a. Chevron Presentation (~5 seconds prior to pull-up)



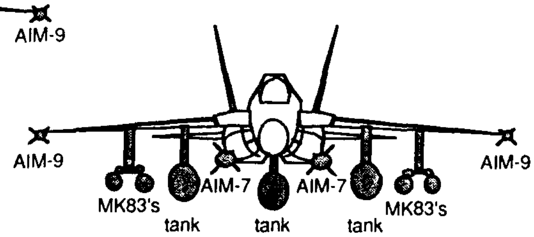
b. Break "X" Formation (at pull-up)

Figure 6

Tested Aircraft Configurations



a. Fighter Escort (FE)



b. Interdiction (INT)

Figure 7

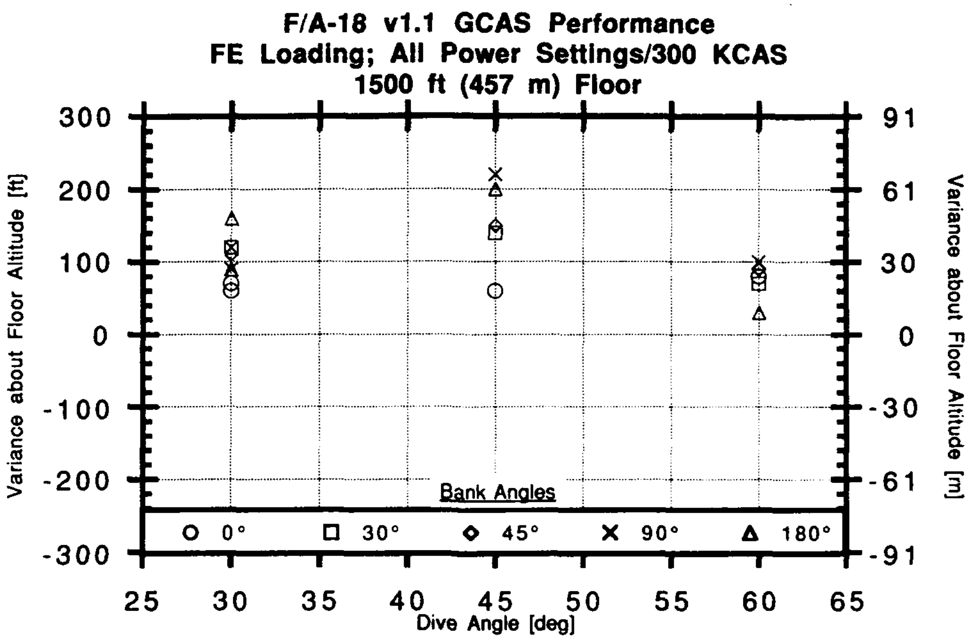


Figure 8

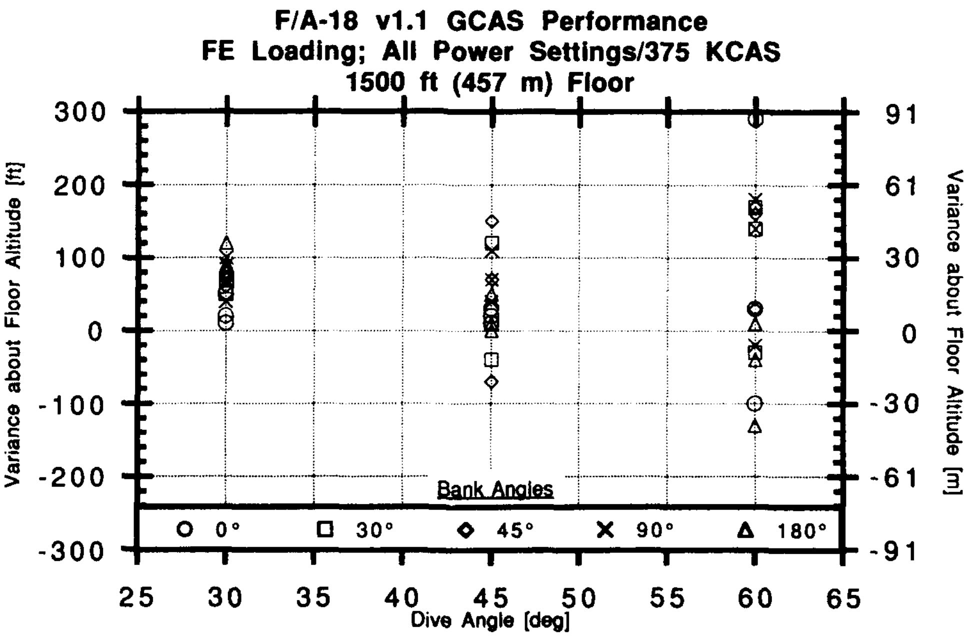


Figure 9

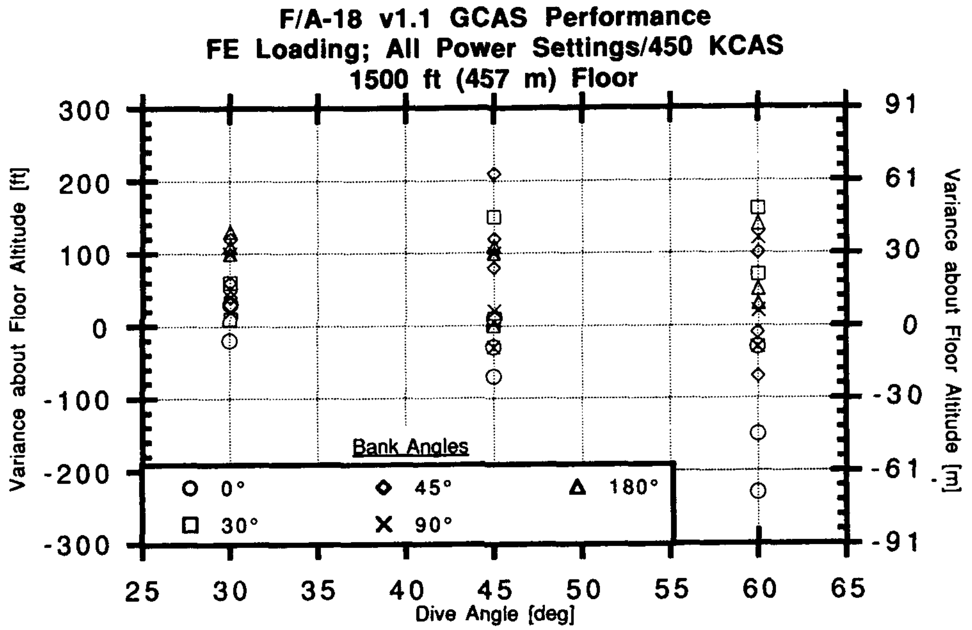


Figure 10

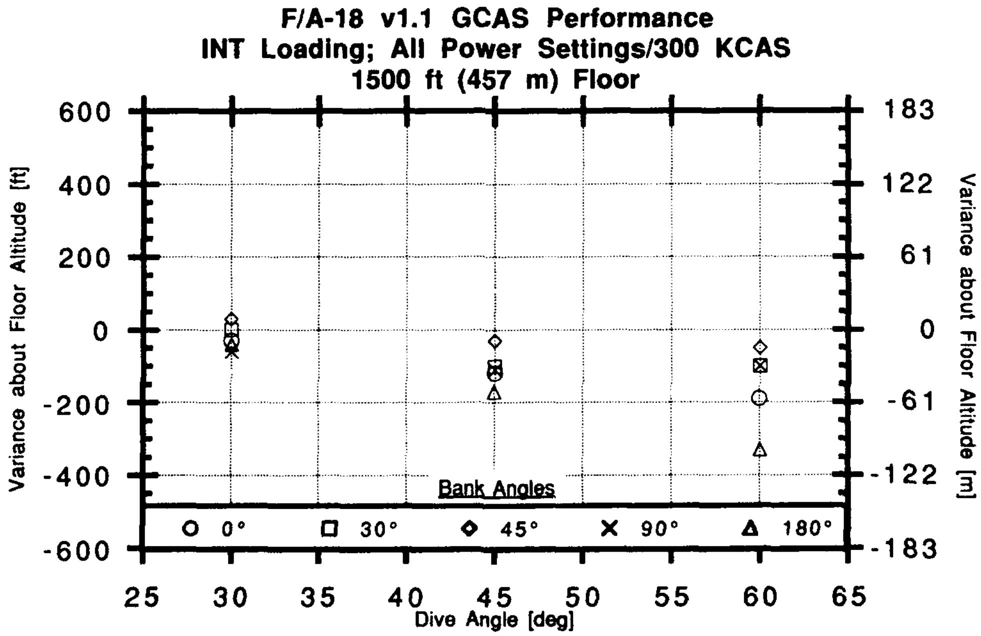


Figure 11

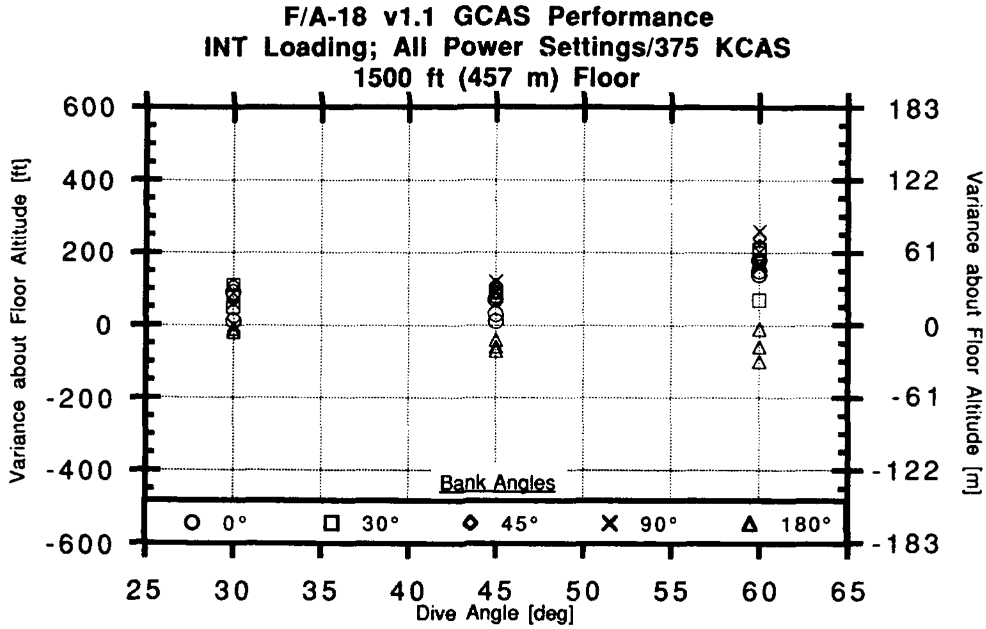


Figure 12

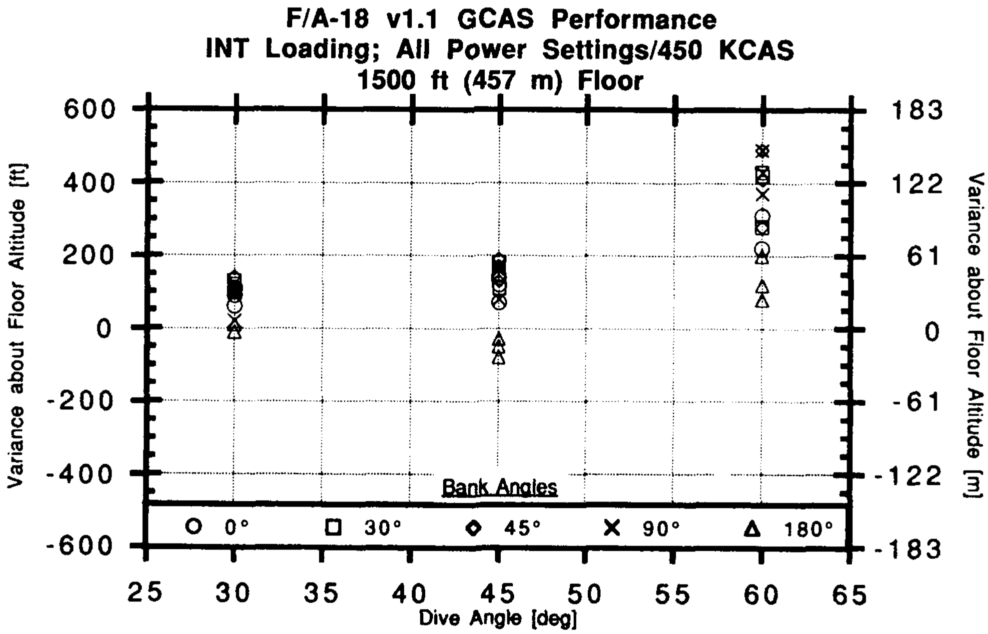


Figure 13

VALIDATION OF SIMULATION SYSTEMS FOR AIRCRAFT ACCEPTANCE TESTING

by

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Chairman FMP Working Group 16 DRA, Bedford, UK

1 INTRODUCTION

AGARD Flight Mechanics Panel Working Group 16 on 'The validation of simulation systems for aircraft acceptance testing' was set up because simulation is starting to play an active role in the certification of some aircraft systems. Yet there is concern that there appears to be no concensus about how to check the validity of such simulations. As Chairman of WG16 it is my privilege to distil the main features identified by individual members into a coherent report. I must however stress that the views I shall express in this talk are my own and do not necessarily represent those of individual members of FMP WG16.

Contributions from WG members are currently being edited to form an AGARD Advisory Report. In this paper I would like to present some thoughts on the use of simulators for flight clearance of systems and aircraft. These thoughts are stimulated by contributions from the experts from many NATO countries who are members of the Flight Mechanics Panel Working Group 16.

First a brief explanation of AGARD Working Groups. These are proposed by the various Technical Panels to bring together experience in the many NATO countries on topics of mutual interest. A Working Group is given 2–3yr to distil this collective experience for presentation as (usually) either an AGARD Advisory Report or a Specialist Lecture Series.

Returning to the subject of validating simulations for acceptance testing, fifteen years ago, with one special exception which will be discussed later, there was no reason to consider using simulation for flight clearance. At that time, as summarised below, aircraft systems were simpler and simulation capabilities were inadequate.

Aircraft	*Simulator*
Simple systems Few critical failure cases	Low fidelity Used for Procedures & sub-set of operating conditions
Regular avionic failures	
All cases cleared by flight demonstration	No need (or capability) for use in flight clearance

There were no good technical or economic reasons for using simulation in the flight clearance process except for one notable exception. Flight clearance of the US NASA Space Shuttle could only be accomplished with the direct involvement of flight simulators because the total atmospheric flight time before the first mission was only 10min (5 landings). Although this is undoubtably a very special case, nevertheless it was the first indication that simulation has a place in flight clearance demonstrations.

2 THE ROLE OF SIMULATION

The current situation already differs greatly. Aircraft system complexity has increased together with simulator fidelity as the following table summarises:

Aircraft	*Simulator*
Complex critical systems Many critical failure cases	High fidelity available in modelling and pilot cues
	Used for edge of envelope investigations
Infrequent avionic failures	
Selected cases cleared by flight demonstration (Most critical & most likely cases)	Used to select cases for flight demonstration and to demonstrate some cases

With many current aircraft it is no longer practical to demonstrate every failure or flight envelope limit in flight tests. Indeed some cases may require encounters with rare meteorological event, that are almost impossible to 'arrange' during development flight tests. This has led to elaborate rig tests such as those for Electromagnetic Compatibility, rather than flight test. Simulation offers another form of 'rig' test.

Development simulators at airframe manufacturer's are already playing a strong background role in many decisions relating to certification, including

a identifying and confirming non-critical failure cases

b developing response procedures for critical failures to be demonstrated in flight

c identifying design modifications to make the severity of failures acceptable

d developing advice on responses to very rare critical cases that are not demonstrated in flight

However, in nearly all cases this still falls short of using simulation for direct clearance of particular situations. The exceptions are manned activities in space such as docking, moon landing, etc where the only possible clearance activities are on rigs and simulators, and a few cases with the latest generation of civil airliners, where the complexity of digital flight control systems and the very low probability of some multiple failure cases combine to provide a powerful case for using rigs and simulation for some sub-system clearances.

The balance of cost and risk for a manned space programme is very different from most military and civil aircraft programmes. However, the lessons learned will be appropriate to such programmes.

The direct use of simulation has not been identified in any military aircraft certification programme, although development simulator tests undoubtably influence the selection of tasks for certification.

If a simulator is to be used for certification then it is essential that it is itself checked to prove that it can represent the certification conditions and the vehicle/system adequately. How is this done at present?

Currently it appears that validity is accepted if the Airworthiness Authority and Manufacturer's pilots find the simulation convincing, and the Manufacturer is confident enough to present simulation as a means of demonstrating aspects of flight clearances.

These are clearly an essential part of any validation, but are they sufficient? Generally the answer is NO, and that is the reason for this WG study. Not only are more rigorous tests required to prove validity, but it is likely that these will increase confidence in simulation capabilities and permit simulation to provide more support in both development and clearance activities.

3 SIMULATION VALIDATION

In considering validation it is important to remember that simulation is the integrated experience of

a aircraft and system models

b any integrated systems rigs

c natural environment models

d military threat environment models

e motion, visual, control loads, audio, etc sensations

f subject pilot

Depending on the task that a simulator is required to perform it is possible to deliberately modify the model or performance of any element, including the pilot. In all cases it is important to avoid modifying pilot behaviour in ways that are unrepresentative of real flight. In training simulators and for secondary tasks on development simulators, it is possible to improve a simulator's acceptability for its primary task by deliberately modifying the aircraft model to compensate for shortcomings in visual or motion sensations. Currently such compensation is 'ad hoc' and frequently distorts other aspects of the simulation. However it is one way of getting acceptance by pilots of simulators for particular training tasks.

This form of compensation cannot be aceptable when a simulator is going to be used to demonstrate behaviour in conditions that will not be experienced in flight. In such situations, which are an essential part of clearance work, the effects of any compensation will be unpredictable. Clearance work is possible only where a simulation can be validated as a known quantity with adequate representation of the required flight conditions.

So what is required for clearance work? Any exercise in simulator validation is essentially one of establishing confidence through a combination of objective measurements and subjective reactions. Subjective views are an essential, if less precise, part of the process because human behaviour is not yet fully understood. (Indeed this is the reason to use manned simulation. Calculation would be adequate if human behaviour could be defined). This subjective element is the main difference between simulation and other rigs, which can be calibrated by direct measurements (although often the knowledge of the underlying natural or man-made phenomena is less precise).

There are several essential ingredients to establish adequate confidence. these must include:

a each element of simulation must be tested individually against measurable criteria

b the integrated simulation must be tested against measurable criteria

c the integrated simulation must be tested by suitably qualified pilots against appropriate flight cases using established subjective assessment scales and comment

d activities where clearance tasks can be adequately simulated must be clearly documented by the manufacturer with supporting evidence

Given these ingredients, then a manufacturer should be in a position to convince the Airworthiness Authorities of the adequacy of simulation for certain clearance activities.

The most important message is that subjective views from pilot's are not sufficient The simulation must be acceptable to the evaluation pilots but this can be achieved by spurious fixes. Only a combination of favourable pilot opinion and objective comparisons with relevant real data is sufficient to establish the confidence necessary to approve a simulation for demonstrating situations for clearance.

Selection of data for objective validation measurements and criteria for satisfactory agreement brings with it a requirement for defined standards on simulation systems quality, and guidance on suitable test data sets and satisfaction criteria. Such guidance should be based on experiences of validation activities on a variety of different simulators and tasks.

Civil airline training simulation specification requirements and simulator certification test schedules indicate the types of standards and guidance that will be needed. They also stress the need for regular checks on simulators to prove that standards are being maintained. Particular areas of concern are

a standards for physical stimulation systems, eg time delays, frequency response, smoothness, scene detail, brightness, contrast, resolution, field of view, etc

b software verification and control, including simulation management as well as models

c flight test data, which will need to include specific test sequences for simulator validation (Data gathered during development flight test is not likely to be sufficient. It may be from an earlier configuration of the aircraft. It may lack test points particularly relevant to particular clearance issues)

d full (non-real time) computer models need to be used to generate data for comparison with real-time models to validate any model compression necessary to achieve real time simulation

An interesting possibility that arises from making each element as 'correct' as possible is the potential for using an additional Training simulator, where detailed representation of the vehicle is essential, as a base for In-Service upgrades (Mid Life Updates). This would require some special features in the training simulator and more rigorous validation, but could well be very cost-effective. It would be important to ensure that such a simulator could accept aircraft electronic equipment, and, of course, such equipment will need to be compatible with simulation functions such as freeze and reset.

A major difficulty will be establishing standards and procedures for military aircraft clearance. However the complexity of military aircraft systems and their operating environments mean that there is much more to gain in reduced costs and development time than there is with civil aircraft. The current squeeze on military funding and the success of 'technology' in the Gulf conflict may provide the incentives to use simulation as a direct contributor to flight clearance. NATO (AGARD) could have a strong role to play in establishing criteria & standards, and in sharing experiences.

4 CONCLUSIONS

There is currently a limited role for simulation in flight clearance of sub-systems in civil aircraft. However the extensive use of simulation for manned space vehicle clearance shows the potential for simulation to join other rigs in flight clearance. There is a serious risk that simulation could prove inadequate if there is no systematic validation programme. Pilot opinion is beguiling but not adequate. Simulation is a complex integration of models of vehicles and the environment, physical sensation devices and the pilot. Any of these can be modified to compensate for inadequacies in parts of the simulation. This can be acceptable for training simulators but is not acceptable for clearance activities because the influence of such modifications cannot be predicted in situations that are not going to be tested in flight.

However, the quality of simulation is increasing rapidly at the same time as the complexity of systems is requiring more extensive flight clearance activity. Now is the time to establish adequate means of validation so that simulation can become an effective part of the clearance process. The standards and procedures used to certify civil training simulators provide a guide for some of the essential features needed for validation. A similar framework is needed for military situations.

Key elements in validation are testing each element and the integrated simulation against objective measures of response and quality, subjective evaluation by pilots, and clear identification of the areas where flight clearance is acceptable using the simulator. Standards are needed for many aspects of simulation and definition of appropriate test data. Experience with the use of simulation in various stages of clearance or acceptance activities will provide the foundation for these standards and test data.

Development of standards and procedures can be assisted by AGARD. New military aircraft and systems have most to gain from the use of simulation in acceptance testing. Their complexity and long costly development all indicate that great benefits can be achieved if valid simulation can be developed and used for acceptance. All the indications are that this is possible already to a significant extent with the advances in modelling and simulation techniques that are apparent from the papers presented at this conference. The pace of development is rapid and it is important to develop standards and procedures now to take advantages of these developing simulation capabilities.

AIRCRAFT SIMULATION AND PILOT PROFICIENCY: FROM SURROGATE FLYING TOWARDS EFFECTIVE TRAINING

by

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Abstract

Simulators are currently build as simple system "look-a-likes" and a structured or experimentally validated approach to their use and implementation as part of a comprehensive training system is lacking. This is one reason why their use in training has not always been as successful as expected. Training time in an aircraft can be reduced to a certain extent, but most often at the cost of increasing total time due to imperfect transfer ratios. The other reason for limited success is that objective and validated indices for performance are rarely available which complicates both the definition of measurable training objectives and the empirical identification of task characteristics critical for skill development. Without objective indices, the issue of "fidelity" versus "validity" remains unresolved.

A missing link between simulator and real flight is the obvious absence of physical danger. Safety serves to reduce anxiety and influences the pilots strategies for task execution. Who's afraid of crashing a simulator? Effects of anxiety on performance could be demonstrated and interactions with high workload conditions occurred. Coping with the mental perils of flight is an important component of pilot proficiency and s(t)imulating such an environment, or at least its impact on performance, is one of the many challenges for the training community.

This paper reviews some experiences with the application of simulators in military flight training and it reports research strategies like the development of objective performance measures in support of validation trials and future simulator development. It is proposed to prototype simulator concepts before implementing them and relevant research initiatives in this area are reviewed.

1.0 Introduction

A major challenge for military aviation to-day and in the near future, is answering the question how to keep operationally effective while training opportunities are more and more restricted. The application of simulation is sometimes envisaged as a ready to go training alternative, but pilots view it as a surrogate for the thrills and perils of real flight. To their opinion, simulation can only be used to provide training support. Environmental pressures and the changing political climate, however, reduce the opportunities for actual tactical flight training. In order to alleviate this potential conflict, simulation and training technology has to be advanced. Multi-disciplinary coöperation is essential and this paper is a first attempt to integrate views of human factor specialists with those of pilots and flight simulation engineers.

2.0 Credibility of simulators: a pilots perspective

Most pilots nowadays encounter a simulator device during various stages of their training. The usefulness of these devices is hardly questioned during the initial training phases that aim to familiarize the pilot with the cockpit and its particular procedures. With more flying experience, however, simulation is likely to be less and less appreciated. Two causes are especially mentioned when one interviews pilots. With more exposure to flying, pilots notice that the simulator cannot reproduce the same sensations as experienced in the air. Secondly, the visual used in nowadays simulators can hardly accommodate the detail required for practising tactical tasks like a Fighter Bomber attack.

Pilots flying the F-16, were disappointed after the introduction of the OFT (Operational Flying Trainer). The expectation was that mission oriented training could be provided, but this assumption was proven wrong and only procedures were practiced. This was a general feeling among F-16 users and the United States Air Force (USAF) undertook action to improve the situation. Visual systems were either added or improved and training syllabi changed. Mission rehearsal had to be curtailed and repetitive single task training was introduced (Martindale et al. 1989). Pilot questionnaires were used to assess the user acceptance of the changed OFT. Adding a limited visual system to a procedure trainer, tripled its acceptance level. Surprisingly, an OFT of a highly agile fighter like the F-16, did not have a visual in the first place. Apparently, the expectation was that most training was accomplished by flying the aircraft. This interpretation is strengthened by the lack of a motion system. Upgrading simulators is a way to improve simulator acceptance but the appreciation is expected to be temporary.

Technology advanced tremendously and better simulators i.e., more sophisticated ones, were built. Pilots are, however, sceptical of their usability for missions and they are clearly anxious about reductions in flight hours to be "cashed in" before simulations are proven effective. In present simulators like the F16-OFT, it is possible for a pilot, even an experienced one, to miss an engine failure for 20 seconds or more, especially when the pilot is absorbed by other tasks. The many cues and sudden on sets of engine failures in

real flight immediately preempt attention to such a major problem. The risk of simulation is that the pilot still wants to comply with the training goals and starts scanning the instruments more frequently (as compared with the aircraft). In that way the engine failure is detected in time and the pilot is not being laughed at by peers or instructors. Such a strategy is understandable, but not effectively transferred in the aircraft. Learning such "simulator skills" is efficient in the sense that they serve to acquire good ratings from the instructor, but such skills are dangerous if they do not apply in the air. In such cases, negative transfer of performance is said to occur.

Why are contemporary simulators configured as they are? Most Air Forces acquire planes, vehicles and simulators through the department of material. These are specialized in hardware purchases, while other departments are responsible for training. Clearly, a cockpit simulator viewed as an airplane without wings, fuselage and tail would serve to familiarize pilots with switches and systems. More advanced training is hardly accomplished on such a device. Furthermore, technical difficulties occur with respect to specifications and requirements. Real airborne systems provide the real thing and could have an economical benefit by sharing the same maintenance with the aircraft. Aircraft systems and displays are, however, intended to be used for a limited number of hours in a flight environment. Many more hours are required in a training school environment. Driving the displays reliably and realistically long enough, creates a considerable need for maintenance and adequate and timely updates of simulation software. This is not easily accomplished.

Up till now, "the simulator" was met with varying degrees of enthusiasm and its role in training systems varied. More capabilities concentrated in a single device increases costs and utilisation should be increased up to 20 hours per day, six days a week to provide some value for money (Shumway 1985). Pilots fear that advanced simulators will be used anyway to satisfy the requirements for cost effectiveness. As long as advanced simulation has not proven its value, pilots advise us to use simple simulators for dedicated tasks.

2.1 Need for simulation

In most cases, one wants to employ a training or teaching tool for the improvement of performance. Typically, this was not the basic intention for using flight simulators. These devices changed the location of practice from the air to the ground. Many advantages accompany that application. Accident rates can be lowered and costs reduced. An average estimate of around 40 - 50% transfer of aircraft time for simulator time has been reported (Orlansky 1989), although many cases of zero transfer occurred. Simulators are recognised for their ability to teach basic procedural skills or the switchology of systems operation. If we could leave it at that, no problem would arise.

Environmental concerns do have an impact on military training. The excercises are clearly visible to the public and observing them would once confirm our deterrence capability, but is now interpreted as a waste of fuel and ammunition. Nuisance for the public is reduced by decreasing noise levels and limiting the amount of low level flying. These developments endanger the proficiency levels of our pilots. What kind of simulators and how many do we need for countering this problem?

A major change is the unpredictability of threats and associated theatres for combat operations. With a lower perceived threat, public support for military expenditures decreases rapidly until new conflicts arise, like those in the Falklands and the Persian Gulf. It was clearly demonstrated that military deployement had to be flexible and innovative in order to serve its purpose. The required flexibility, stresses the importance of, and need for, more advanced simulation facilities. Mission planning and mission execution should be practiced in environments modelled rapidly from photographs, intelligence data, etc. The alternative of using aircraft for these purposes, is unattainable by environmental, economical and political reasons. Night flying with fighters at low levels with Night vision goggles or operating helicopters with Forward looking infra red displays (FLIR) is hardly acceptable for the general public. Simulation, therefore is here to stay and time in the aircraft will be diminished anyway. Pilot opinion will not suffice to change this trend.

Simulators were initially used as simple "system replacers" and a structured and experimentally validated approach to their use and implementation as part of a comprehensive training system is still lacking. Present procedures in determining requirements for simulators recognize that training analysis is needed to identify the training tasks to be performed. Subsequently, a matrix is composed by adding possible devices like simulators, computer based instructions, cardboards, etc. "Ticking the boxes", will match capabilities to training tasks. The decision criteria in such an approach are costs and a minimal number of devices. It is based on the assumption that costs provide the major criterion for designing a training system. Buying the cheapest device is a familiar trap, "only to find that the simulator fails to meet requirements that were poorly understood in the first place". (Warwick 1990).

Training task definition is a necessary but not sufficient step. An additional step that has to be undertaken is a translation of training tasks to a skill specification. This is not easily accomplished. Imagine the training task of "aircraft handling within the operational flight envelope" and its meaning for skills involved in flying the Airbus A-320 versus the F-16. Both have fly by wire technology, but training needs are quite different.

Two strategies can be used to come to a skill specification. The first is asking pilots for a definition and let them provide a rating or level of accomplishment for each particular device or training aid. The second one is basic research into the learning process itself with the purpose of providing measurable objectives for training programs to accomplish.
The first problem is to decide whether pilots are aware of their skills. The second one is that pilots should have actual experience with advanced simulation technology in order to be able to compare demands with capabilities realistically. Most often both requirements are not met. The definition of training requirements and simulator specification is complex and requires the work of many disciplines in a coordinated effort (For an illustrative discussion, see Bass 1989). Coordinated research programs can serve as a guideline

for those teams. The problem is who is going to initiate and fund such programs? The suppliers of simulators, the buyers or both?

2.2 Pilot proficiency

The introduction of vehicle simulators and other expensive training devices did have, if all others fail, one major benefit. It stimulated the general interest in effectiveness. Flight training itself, should not be regarded to be perfect in the first place. When asked to define the required simulator and aircraft hours for optimal combat proficiency , helicopter pilots responded that present training is insufficient and does not provide enough pilots with acceptable levels of proficiency (Dees & Byars 1987). Adding more simulator technology would in their view, simple be "additional training added to a suboptimal training program".

Researchers involved in evaluating simulators, discover very quickly that a fundamental or systematic basis for the training is often lacking. It is also discovered that many unknowns exists in military training procedures. One reason is that jobs are regarded to be dangerous and training is based on operational experience and expertise of instructors with combat exposure. Many skills are poorly understood, let alone their most appropriate training method. Any improvement in training effectiveness that occurred during the process of re-thinking procedures for incorporating a simulator, could leave little or no credit to the simulator.

An example of a poorly understood skill is Air Combat Manoeuvring (ACM). Ideally, one would be able to teach all, or at least most pilots, to pull the job. However, experiences of commanders in the field show, and this is even observed during realistic exercises like Red Flag, that "10% of the pilots are responsible for 90% of the hits". These findings reinstigated research within many Air Forces into personality characteristics of combat pilots. Factors like "risk taking" and "coping" could make the difference between pilots, equal in competence or flight-experience otherwise. Without sufficient insight in the complexity of skills involved in ACM, it is hard or useless to try to specify a simulator. Additional "in-training" research is needed and the introduction of "Air Combat Manoeuvring instrumentation" can contribute by providing data for the analysis and specification of skills.

3.0 Human Factors

Simulators have to be valid in the sense that they provide "transfer of performance". Performance for a skilled operator is the result of two factors:

1. Quality of task execution i.e., procedures in information processing and use of correct strategies;
2. Level of task involvement, i.e., executing the necessary effort, a motivational aspect.

Both factors are well researched within "human performance theory" that describes the mental capabilities of a pilot or other operator as an information processing system with a limited capacity of mental resources. The availability of these resources is dependent on energetical mechanisms that are influenced by stress and emotion or factors like physiological fatigue and sleep deprivation. Performance decrements can be counteracted by motivation and effort. Additionally, the adrenalin is keeping regular performance at high levels.

Task execution: for a similar execution of a task, the simulator should provide the same information as used in the aircraft. If it is lacking, no similar strategy is to be expected. Alternatively, information can only be left out if one knows that the particular information is not used to accomplish the task. Research is typically oriented at assessing the required level of "fidelity" for a simulator device. Human Factors issues within this area are: benefits of motion cueing, visual-motion a synchrony, seat cueing, visual requirements, etc.

Task involvement: a simulator should provide sufficient "realism" to induce the pilot to spend his mental resources to the fullest. Motivation, face validity (simulator looks like aircraft) and knowledge of results, i.e., feedback of performance by system or instructor, serve to keep spirits high. No device will provide adequate performance without a willing operator. Lack of risk will reduce the stress level as compared with flying. A new risk is that strategies will be learned in the simulator that cannot be used in stressful "real live" operating conditions. In that case "simulator skills" have once again been acquired.

An example of typical research in the area of task execution is the study of time delays between pilot inputs and simulator system responses and their impact on pilot control strategy. Increased time delays result in unstable vehicle dynamics and pilots have to exert more control effort as indicated by Power spectral analysis (Middendorf et al 1990). Cost reductions serve to drive the studies towards a trade-off between various cueing systems. Is an advanced motion system required when one has a wide field of view visual system? Most studies involve simulator-to-simulator transfer designs for practical reasons and actual comparisons with in-flight measurements are very rare indeed. This is a critical flaw in the research and it should be corrected whenever possible.

Pilots' statements about "the thrills of flying" or "seat of the pants" indicate that a certain redundancy in information is critical. Multiple channels of information can speed human information processing, but they also provide means for restricting interference while processing in multiple task situations. Visual and vestibular systems are complementary in their sensitivity and frequency response. Visual information is particularly effective for slowly changing scenes, like adequately demonstrated by wide screen cinemas with movies filmed out of balloons. Vestibular cues are particularly effective at higher frequencies and can serve as attention getters. Anybody flying a single engine aircraft like those used for basic flight training, knows how effectively these cues are for correcting (instinctively?) the turbulence encountered during approach and landing trials.

Pilot comments, or comments attributed to pilots by somebody else, are often the only evidence for the presumed realism of simulation. Pilots flying simulated military missions perspire as much as in the aircraft, but such an observation can hardly be taken as a proof of concept. Alternatively, in civil aviation stories go around about a pilot who tried to phone his wife after diverting to London in a simulated flight. These casual observations are about the only evidence that "task involvement" is to be expected in

simulations. However, more objective means for assessment are rarely employed.

Fidelity of technical simulation is required to obtain the appropriate human strategy of task execution. Validity of simulation is obtained whenever pilots behave the same as in the aircraft, i.e., realism is high enough to include levels of task involvement comparable to those in the aircraft. After that, training schedules etc. determine the effectiveness of skill acquisition.

3.1 Realism in simulation: a comparison with the aircraft

Human Factor Studies comparing the simulator directly with the aircraft are very rare. Psychophysiological measures like heart rate and respiration can be used as practical indices for workload and stress and they serve to visualize the "task involvement" of the pilot. Stress in examinations raises heart rate and reveals a continuously activated mental state irrespective of demands from ongoing tasks. Coping with stress reduces this "over activation" and means progress in training. Individual differences in proficiency can also be detected and compared (Jorna and Moraal 1986).

In-flight data is hard to obtain and so far only the Human Engineering Laboratory of Wright Patterson succeeded in measuring heart rate in both the aircraft (A-7 Corsair) and its corresponding simulator. We could use their data and analysed flight tasks selected to have a reduced possibility for physical biases in heart rate as caused by G-factors. The study compared in-flight responses with those in the simulator.

The results depicted in fig. 1 show certainly no promise for the use of this simulator as a replacement of the aircraft. Heart rate revealed a consistent sensitivity to flying tasks as well as flying in the lead or wing position. The simulator did not succeed in copying this pattern.

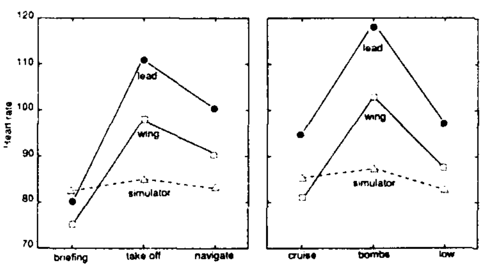

Fig. 1 Heart rate for pilots flying both the A-7 aircraft and its corresponding simulator

An important question with respect to the validity of simulation is whether a lack of realism as indicated by the heart rate study, influences the way pilots execute their tasks. The answer to this question is yes, and will be illustrated by discussing a study that addressed the effects of anxiety on pilot control activity (Jorna & Visser, 1990). Power spectral analysis was used to analyze control inputs (ailerons) while flying a standardized pattern. Two groups participated with either a "high" or "low" level of anxiety. The assumption, according to human performance theory, is that "worry" will occupy mental capacity that would otherwise be used for task related information processing like that associated with control activity. Both groups were matched on relevant factors like experience, psycho-motor ability, age, etc. The results obtained with power spectral analysis are depicted in fig. 2.

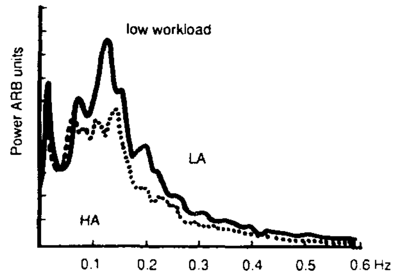

Fig. 2 Effects of anxiety level on control activity as assessed by Power spectral analysis of aileron inputs.
HA - High Anxiety subjects, LA - Low Anxiety subjects. ARB - Arbitrary units

Systematic differences in control strategy were found as a function of anxiety level. Note that pilots represent a pre-selected subgroup and that anxiety levels have to be regarded as minor if compared to a non-selected population. Consequently, even small differences in anxiety level seem sufficient to influence control activity. The effect of anxiety was more pronounced when the subjects were tested under high workload conditions. When the same mental capacity is affected by both anxiety and workload, than the difference between groups should increase as compared with low workload conditions. This effect, a so-called interaction between level of anxiety and task demand, was confirmed and is illustrated in fig. 3.

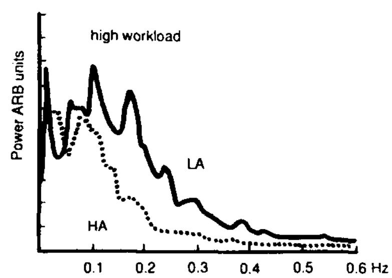

Fig. 3 Power spectral analysis of control activity while flying with additional tasks to be performed.
HA - High Anxiety subjects, LA - Low Anxiety subjects. ARB - Arbitrary units

Realism in simulation is expected to improve task involvement of pilots. Anxiety or flight related stresses represent a missing link between simulation and actual flight and pose a major area for research. Its subtle consequences can be revealed by fine grained objective indices of performance. The lack of risk can also change performance strategy more crudely. When observing pilots during simulated flight, one can often note that pilots try to accomplish "impossible" landings. When inquired about their behaviour, all pilots

assure that they will never take such risks in actual flight!

3.2 Towards effective training: human resource management

Clearly, the impact of simulators on the training community and associated industry has been quite substantial. Many interesting questions and issues arose but the initial enthusiasm and expectations concerning simulators has cooled down a bit. However, major changes in training demand are to occur and a policy for design and use of simulators has to be developed. The need for guidelines is urgent. Some industries are even reluctant to develop new simulators as there are no established criteria for proving their performance or establishing "legal" compliance with the requirements of a training system.

Integrated training concepts with simulators are welcomed, but the purpose of training is wider in the sense that also sufficient number of operators have to be delivered. It is therefore necessary to broaden the scope on the role of training in accomplishing that requirement. A military weapons platform sets a particular demand for human capabilities. This demand can be met with varying degrees of success depending on 1) the complexity and design of the system 2) the ability of the operator and 3) the level of training. These factors are interrelated as illustrated in fig. 4. This "performance circle" maps the demands in relation to the needed human capabilities.

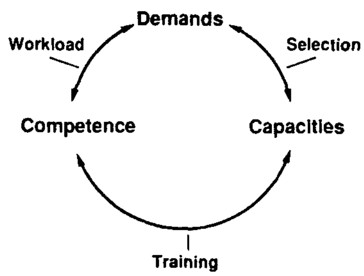

Fig. 4. Relation between task demands, basic human capacities and operator competence in meeting task requirements. The higher the competence level of the operator, by either training or selected aptitude, the less the experienced workload.

Selection of aspirant pilots is commonly accepted as essential for later performance levels. The purpose of selection is to increase the number of student pilots that pass training, or with a longer time perspective, provide pilots who function effectively under operational circumstances. Selection psychologists need a performance criterion to predict. This criterion performance itself will, however, be determined by many factors like the quality of training that aspirants will receive. Pilots with a similar license still differ in their level of performance for particular tasks. The competence level will influence performance efficiency and workload while meeting system demands. It depends on both training and individual abilities. The circle illustrates that 1) training is only a part of a personnel management system, 2) training levels and workload are interrelated, and 3) individual differences between pilots are relevant at all locations. Taken together, the output of a training program is a certain number of operators with a particular minimum level of competence or proficiency.

For most training systems base line information on the skill acquisition process is not available. There is hardly any insight in the actual trade-offs between performance levels, workload involved and their relation with training time, let alone training devices. "In training" research with operational vehicles and aircraft provides that base line information. The steps in identifying the "learning curves" are summarized in table 1.

Table 1. Steps in identifying basic learning process in current training procedures

1	Task specification
2	Working conditions
3	Performance and workload measures
4	Assess learning process
5	Assess individual differences
6	Determine training time

The advantage of training analysis with performance based criteria instead of task specification is that the tasks have to be mapped to skills, in order to define their performance indices. If one is not able to define performance indices, task analysis has failed and the skill(s) involved are not clearly understood. If the analysis or assumptions prove right, some learning curve should be found and adequate performance feedback (specification of a simulator subsystem) can be determined to improve efficiency of skill acquisition.

Learning is not always reflected directly in a performance measure, as it can also affect the performance/workload relation mentioned earlier. *After practice a lower workload is involved in* achieving the same level of performance. Both indices must be included in studies of pilot behaviour and performance. This "two factor approach" to skill analysis is illustrated in fig. 5.

Fig. 5 Two factor approach in skill analysis for designing training programs.

An advantage of the "in training" research strategy is that present training policies can be optimized independently from changes introduced by simulators. In many cases, issues like inadequate *training syllabi*, *inconsistent training goals*, lack of scenarios, predictable training tasks, too short training periods and inefficient transfer to advanced training levels can be identified beforehand and improved upon by restructuring training procedures.

Performing in-training studies is therefore urgent, as the opportunities for obtaining "criterion" information on the real system are diminishing rapidly.

3.3 Simulators: for what purpose?

In deciding on the use of a simulator, one was *traditionally bound to think in terms of* a replica of an aircraft or other vehicle. It is misleading to assume that for fidelity reasons simulators must be look-a-likes and that training device specification only requires the add-on of an instructor station. It is important to consider that different "training pipelines" do exist within military training programs. Some of them and their associated research areas are summarized in figure 6.

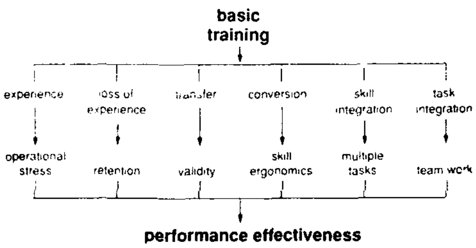

Fig. 6 Training pipeline diversification after basic training and associated research areas. Training serves many intentions, each with specific requirements for simulation devices or training technology.

Experience: Traditionally most programs involve extended training and practice to gain experience. The purpose is to increase proficiency and "spare capacity" in particular, in order to be able to perform under operational (combat) stress. In aviation, a simulator would include mission oriented practice with associated threats, etc. Coping opportunities with danger are not provided by simulation. Typically, pilots are anxious about loosing flight time to an advanced simulation facility. Alternatives have to be investigated.

Loss of experience: All pilots will encounter a point in their career where there is no time for flying regularly. Retention of skill levels is a positive output for any training program and could serve as a quality index. It would be interesting to assess the minimal actual flight time that is required to obtain "combat readiness" after synthetic training with advanced simulators.

Transfer: Transfer of training, or more accurately, transfer of performance, is what it is all about. All pilots have to transfer from simulators to real aircraft. Factors influencing transfer are not well understood yet.

Conversion: Typical transition from one aircraft to another aircraft. Of special interest are *issues like the effectiveness for later "fly by* wire pilots" to accommodate old-fashioned aircraft during basic training. Similarly, helicopter pilots are trained fixed-wing but serve under totally different operating conditions. In what way can simulators contribute to facilitate direct training?

Skill integration: Nobody learns all tasks at the same time. Part-task simulators are likely candidates to serve a breakdown of learning tasks, but general hesitance is observed in actually procuring them. The issue is first to decide wether it makes sense to procure a part-task device for training component skills and secondly to decide *on the point in time that training integration* should occur. To what extent can partial or component skills be identified that are independent of the context in which they have to be executed.

Task integration: An issue that was intensly debated while determining crew concepts for armed helicopters. Some tasks have to be integrated either in a crew or within a person. Should navigation be performed by a commander/ gunner in a two-seater, because of excessive pilot workload, or should the pilot in spite of workload be continuously aware of his position i.e., perform navigation himself. Teamwork is definitely essential to operational effectiveness of multi crew gunships.

Even from a limited overview it is painfully clear that the era of "the single simulator" has ended. Special purpose simulations will have to be developed to serve dedicated and independent applications within a *training* program. *The* result is a mix of simulators or a family of "trainers" optimized for particular skills like terrain navigation, electronic counter measures, refuelling, etc. An integrated simulation should be available to learn the pilot that the strategies used to solve a particular sub-task will have to apply when other duties have to be performed concurrently. "Backward chaining", a technique showing intended criterion performance before practicing components, represents a view compatible with such a training setup. The diversity of possible training tools makes it impossible to build and test all devices. Therefore, a generic reconfigurable high quality simulator facility would serve research in this area.

4.0 Simulation engineering

4.1 Test beds: validate before fabricate

The design process for aircraft is paved with detailed design reviews, testing, modifying, testing again and finally many, many flight tests. This in contrast with the design of a simulator. The approach in that case is to build a marketable product to the customers, who in case of military aircraft, represent the Ministeries Of Defence (MOD). For consumer goods one can describe the functions and related benefits, but the output of a simulator is not so easily defined. One would expect the output to be a skilled operator, but this product is the result of a synthesis between the simulator and its user i.e., the manufacturer and the MOD. Typically, simulators are not tested training wise before being put into service. It is only after the synthesis has occured that problems are detected. An

alternative is to "flight test" the simulator itself. In flight studies that allow a direct comparison with simulated flights are very helpful as will be illustrated by examples from NLR research.

The importance of presenting pilots with the appropriate information or cue's is well recognized but critical details are easily overlooked. The first example concerns a programme performed to develop low-speed handling qualities criteria for transport aircraft with fly-by-wire flight control systems. After ground-based simulator trials USAF's Total In-Flight Simulator (TIFS) operated by the Calspan Corporation was used for validation purposes. Cooper-Harper ratings (subjective measures on controllability) and comments of pilots were compared for the in-flight and ground-based experiments. It appeared that the application of Direct Lift Control did improve pilot ratings in the ground-based simulator while it did not in the in-flight implementation. It turned out that pilots complained explicitly about disturbing heave motions in the in-flight situation. In the ground-based simulator these heave responses happened to be attenuated by the filters of the motion system. Thus a potential real flight problem was masked in a ground-based experiment [illegible].

An other example concerns the importance of providing pilots with multiple cues and is based on the LAVI-project in which NLR's simulator served the ground-based role. During the development of the advanced fly-by-wire flight control system flying qualities evaluations were performed with a moving-base. The single-seat cockpit was equipped with g-suit capabilities and it flew both air-to-air and air-to-ground missions. A great deal of attention was devoted to the right <u>timing of multiple cues</u> like motion, g-suit, vision, HUD, instruments, noise, in order to assure that all of them are working on the pilot in a coordinated fashion. No simulator sickness was observed!
After the ground-based experiment a smooth transition to the in-flight test program was accomplished using Calspan's TIFS. "The simulated aircraft flew like the simulator" was a complex comment but still very much appreciated.
Subsequently, the transition to the LAVI-prototype was easy. Flight tests of other prototypes with advanced fly-by-wire flight control systems were less succesful (F-16, F-18, Gripen).

Thorough testing is essential in procuring a simulator as a product with a reasonable chance of success. We propose that simulator concepts should be <u>prototyped</u> and their capability for generating a learning curve <u>demonstrated</u>. With the costs of simulators rising beyond those of the aircraft, and taking into account the exploitation costs, the importance of adequate validation studies is stressed and their cost effectiveness assured by definition.

Up till now, the research simulator of NLR played a systems oriented role concerning pilot-aircraft interaction, with topics like handling qualities research, man-machine interfacing, advanced flight control system development, operational procedures development, and avionics integration. The most recent policy paper of the Ministry of Defence indicates the growing concern for the living environment in our small country with its high density of population. That concern stimulates an intensive development and application of technology for training simulators. This year an important milestone was achieved, with respect to the development of a highly flexible simulation facility, that creates new research opportunities for Defence and Industry:

a) Development and evaluation of new system concepts: the timely evaluation of crew stations under simulated operational circumstances.
b) Research of possibilities and tools for training simulators, prototyping of new training systems resulting in straightforward simulator specification, support of existing elements in training programs.
c) The generation of environments for operational applications i.e. developing new tactics.
d) The availability of a powerful training facility for the evaluation of special scenarios.
e) A "testbed" for industry in the phase of development of aircraft [illegible] for aircraft, helicopters and their corresponding training simulators.

The new high performance 6-DOF motion base, made in Holland, forms the part that is physically in at present. The completion of the facility is foreseen in a two-step approach. After the realisation of step 1, advanced fighter simulation, in particular F-16, is achieved. An F-16 "Mid Life Update" cockpit, fully operational and equipped with g-cueing, is placed on top of the motion base and is surrounded by a dome for displaying outside vision. This step will require about two and a half years. The second step expands the simulation towards helicopters, armoured vehicles and special ships, making use of newly developed generic "panel and display" concepts and software models.

It is realised that a multi-disciplinary approach is necessary for constructing cost effective training devices and associated training procedures. Research tools are needed in the field of human factors concerning the measurement of performance and workload, pilot [illegible] combined with [illegible] to prototype and evaluate [illegible] of a training system.

[illegible] Research initiatives

The need for training related research is clearly recognized within the European [illegible] community. First, there is the initiative [illegible] the [illegible] collaboration [illegible] the IEPG (Independent European Programme Group) [illegible] the EUCLID (European Cooperation for the Long Term in Defence) program the subject of Human Factors and simulation was added to the list of CEPA's (Common European Priority Areas) [illegible] Netherlands initiative.
This area now reads: "Technology in the Field of Human Factors including Simulation for Training Purposes" and contains two related RTP's (Research Technology Projects) both focussed on possible solutions of the problems indicated before. These RTP's are:
11.1 "Training system concepts for simulator-based military training"
11.2 "Simulation Techniques"

Secondly, AGARD self took the initiative for a workshop on "Low Level Flight Training". This workshop resulted in the composition of the Terms of Reference for AGARD's "Aerospace Applications Study 34". Reduction of the environmental impact of operational flying training, particularly low level, also adresses the subject of simulation

the study group held its third meeting this summer, the final report is expected in 1992. The available time for this study was extended in order to enable the incorporation of the first evaluation results of the upgraded Tornado and Harrier GR5 simulator. We are looking forward to the results of this Group. Thirdly, there is the Working Group 20 of the Flight Mechanics Panel on the subject of "Piloted Simulation in Low Altitude High Speed mission Rehearsal"

All these initiatives are clearly welcomed and appreciated but they will all suffer from a lack of base line criterion information on the skills involved in operating agile fighters in dangerous environments. Two additional research initiatives are therefore proposed: first a coordinated effort among NATO air forces to acquire data and collect basic learning curves for pilots. This task will be difficult but not impossible when it is structured around common needs and objectives within pilot training. The second initiative is testing and prototyping simulators derived from or modified, by the results of those studies.
If coordinated research is to succeed, some cooperation has to be established between manufacturers and users, despite their different goals associated with selling and buying.

A trend emerging is to procure aircraft with their training system in one integrated package. No standards or verifiable requirements are available yet. That omission is not only risky from the point of view of cost effectiveness, but moreover, risky for the pilots. They have to survive and perform in an unpredictable, but still high threat environment. Surrogate flying is not easily transferred into effective training, but a major AGARD coordinatory effort could assist in accomplishing just that.

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The Use of a Dedicated Testbed to Evaluate *Simulator Training Effectiveness*

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1. SUMMARY

The Simulator Complexity Test Bed (SCTB) is being produced for the U. S. Army Research Institute Aviation Research and Development Activity (ARIARDA) at Fort Rucker, Alabama to specifically address the question of the level of simulation fidelity required to ensure adequate transfer of training in a tactical helicopter simulator environment. This paper presents the objectives of the SCTB, the hardware and software architecture designed to facilitate these goals and presents examples of some typical research that will be conducted. The simulator is based on the Apache AH-64A attack helicopter using aircraft parts and simulated avionics to provide a realistic replica of the pilot and copilot gunner positions.

2. SCTB RESEARCH OBJECTIVES

A major impetus for the development of the SCTB was the criticism of the general lack of quantifiable data regarding flight simulator training effectiveness. Issues such as the relationship between training transfer and fidelity, the minimum essential elements for a simulator or training device to effectively train aviators for individual and collective tasks in a doctrinal environment and the increased emphasis on training devices and simulators for sustaining readiness remain unresolved. The objectives of the SCTB are to investigate these and other issues and are the following:

(a) The empirical definition of training device requirements, desk top through full mission simulator, for maintenance of combat readiness of Army aviators

(b) To quantify factors impacting on training transfer - fidelity relationships

(c) Tactics and doctrine development through systematic man-in-the-loop scenario simulation

(d) User-driven exploration of impact on combat effectiveness of potential new ROCs for aircraft

(e) Hardware test bed for man-in-the-loop simulations in a combined arms environment

3. SYSTEM ARCHITECTURE

3.1 Hardware

The building blocks of the SCTB, provided to address the research objectives, are shown in Figure 1 and are described briefly as follows:

(a) Pilot Station. The pilot station has been separated from the copilot gunner station to facilitate the expected experimental requirements. The cockpit shell is built from a damaged helicopter and has been mounted on wheels so that it can be mated with various visual display systems. The cockpit instrumentation incorporates aircraft parts, where required, while processors in aircraft avionics have been simulated to allow future modification.

(b) Copilot/Gunner Station. The copilot/gunner station has been built following the same guidelines as the pilot station. In the case of the aircraft optical relay tube (ORT), the aircraft electronics and displays have been replaced with commercial equipment to provide multiple line rate displays and reduce the life-cycle costs.

(c) Fibre-Optic Helmet Mounted Display (FOHMD). The FOHMD is the primary visual display device on the SCTB. The system block diagram is shown in Figure 2. The FOHMD provides a virtually unlimited field of view as well as a higher brightness and contrast image than any previous display devices. System performance specifications are shown in Table 1.

(d) Alternate Display. The alternate display consists of three back projected screens providing a field of view of 120 degrees horizontally and 60 degrees vertically. Each screen is driven using a separate channel from the ESIG-1000 image generator.
The projectors used provide a resolution of 1280 by 1024 at 60 Hz interlaced.

(e) Experimenter/Operator Station (EOS). The EOS is shown in Figure 3. From the EOS, the experimenter can control and monitor the execution of the experiment. The station comprises two RISC-based graphics workstations which provide high-resolution graphics for real-time display of experimental data. This data consists of both text and graphical information and is presented in a window environment generated from the workstation graphics library. The graphics editor on the EOS allows the experimenter to create displays that are representative of vehicle equipment.

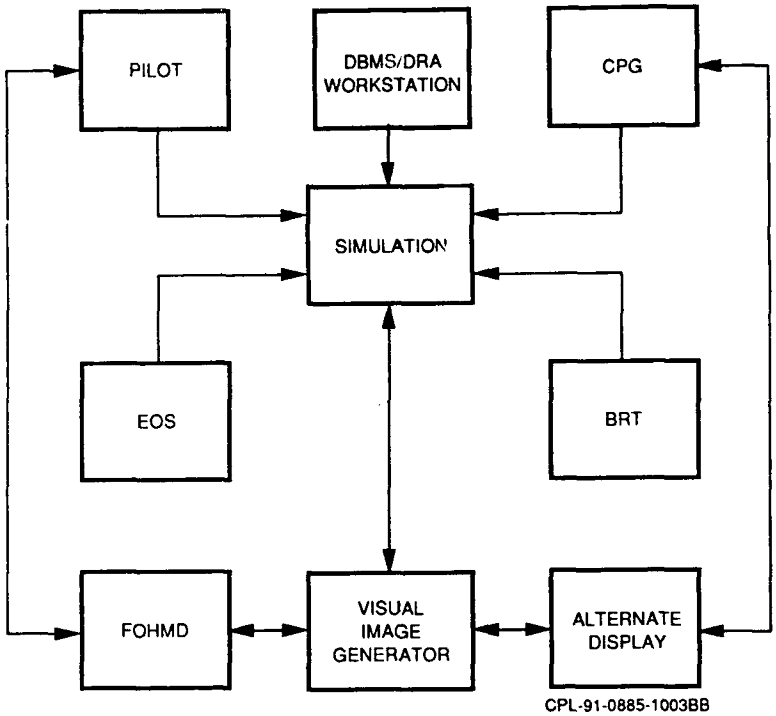

Figure 1 SCTB Objectives Block Diagram

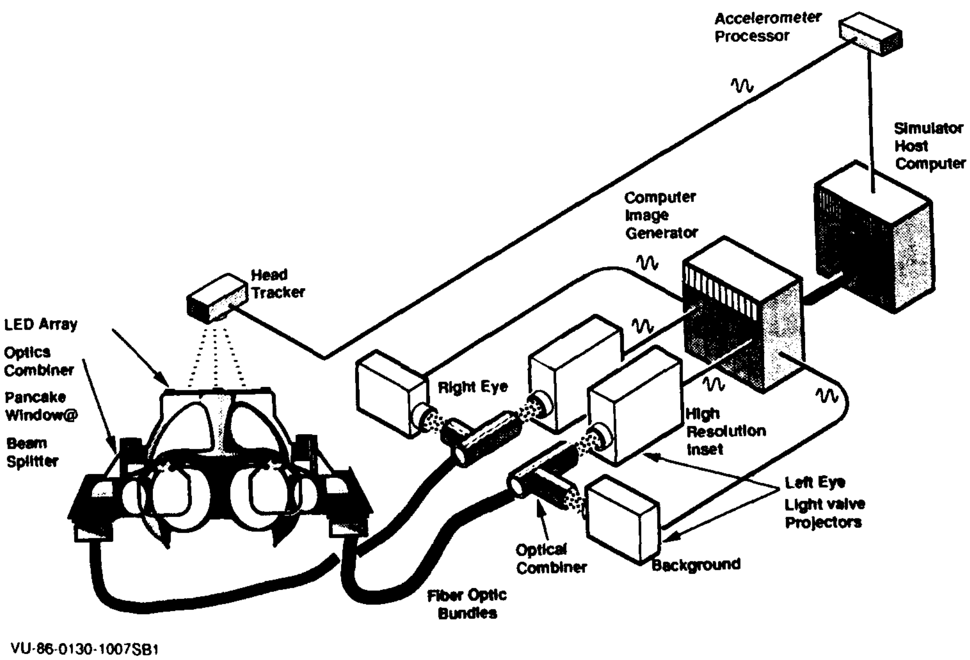

Figure 2 FOHMD System Components

TABLE 1

FOHMD SPECIFICATIONS

FOV (INSTANTANEOUS)	
BACKGROUND	127° x 66°
INSET	25° x 18.9°
BRIGHTNESS	> 50 FT LAMBERTS
CONTRAST	50:1
RESOLUTION	
BACKGROUND	5.0 ARC MIN/TV LINE PAIR
INSET	1.5 ARC MIN/TV LINE PAIR

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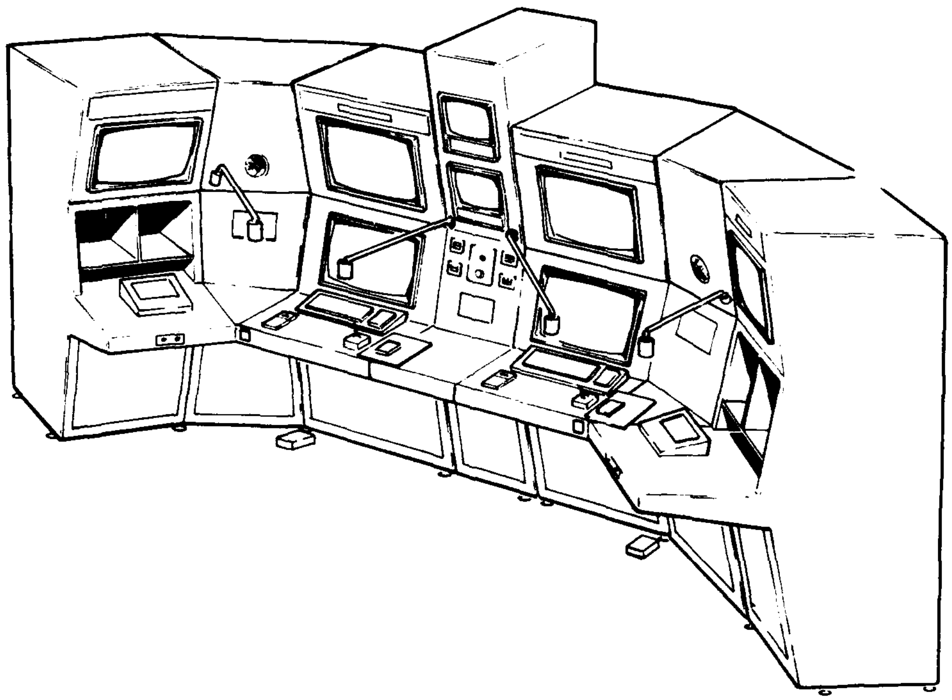

Figure 3 Experimenter/Operator Station

Typical examples are aircraft MFDs, analogue instruments and HUD symbology. These displays, in conjunction with simulation software, can be used to design various levels of training devices which can then be evaluated for training effectiveness.

(f) Interactive Tactical Environment Management System (ITEMS) Data Base Management System (DBMS) and Data Recording/Analysis (DRA) Workstation. The DBMS/DRA workstation has two functions. First, the tactical scenarios that are used in experimentation are generated using the ITEMS package. Second, the experimental data generated on the real-time system is analyzed using the DRA analysis package. The workstation is a RISC-based architecture with sufficient peripheral capacity to support scenario generation and data analysis.

(g) Blue/Red Team Station (BRT). The BRT is based on the same workstation as the EOS. The purpose of the BRT is to provide the capability for human intervention in an experimental scenario. The BRT has an "out of cockpit" view and a "stick and throttle" for control. Any player in a scenario can be controlled from the BRT. The BRT player normally operates automatically in the scenario, however, any selected player in a scenario can be controlled from this station.

(h) Host Computer. The host computer and its associated interfaces are shown in Figure 4. The selection of the host computer was made after a study of the available computer architectures. The requirement was that the system is tightly coupled yet still provides the flexibility to allow the reconfiguration needed for the experimental goals. The host computer consists of three separate groups of 4 RISC-based CPUs with the associated peripheral devices. Each CPU resides on a high bandwidth system bus to which system memory is also connected. This architecture provides the tight coupling to adequately simulate time and sequence critical tasks, such as man-in-the-loop systems, while still providing for the necessary modularity. Communication between the units is through a reflected memory board which resides on the VME I/O bus of each of the three units. The transmission medium between the boards is a fibre optic cable. These boards also provide for synchronization of the separate units. The start of frame signal is generated from a 60 Hz interrupt received from the image generator. The computer peripherals include the usual disks, tape drives and terminal ports but also include two 1.2 G-byte, 8-mm tape drives used for data recording. The 8-mm tape drives, coupled with newly developed software, provide for virtually unlimited recording capacity.

(i) Visual System. The visual system on the SCTB is the Evans and Sutherland ESIG-1000. It comprises a host computer and image generator. The host computer provides for the interface to the simulator host computer and also runs real-time software controlling visual features as requested from the simulation. The image generator contains 10 channels of video data and one channel of LOS data. The 10 channels of video are used as follows:

- Four channels, high-resolution inset
- Four channels, lower resolution background
- Two channels infrared

(j) Visual Data Base Modelling Workstation. This workstation is provided to modify existing ESIG-1000 data bases and to create data bases for future experimental requirements.

3.2 Software

The software architecture on the SCTB employs a mixture of old and new techniques. Software used on numerous flight simulators has been used in conjunction with new approaches to unique problems associated with the experimental use of this device.

(a) Operating System (O/S). The O/S used on the host computer, and all other computers on the device, is UNIX. This is the first major application of this O/S on a high fidelity flight simulator. While UNIX has not been considered suitable for real-time applications, significant work by the vendor and CAE has produced a system that is reliable, deterministic and provides the required timing and interrupt response for simulation fidelity.

(b) Utilities. To provide an effective user environment, beyond what is provided with UNIX, a number of software utilities were developed or ported. The list that follows describes utilities that are used to provide the flexibility required for this program.

(1) SIMEX-Plus. While not its only function, this utility provides the configuration management and reconfiguration capability which is fundamental to the successful use of the SCTB. The configuration is controlled and maintained to the software module level, a module being defined as a disk file. The reconfiguration capability is built from this management tool. For example, an experimenter can build a software load module that is unique. It can then be modified, updated, reorganized and maintained separately from other experiments. The utility provides tools for comparing load modules as well as maintaining revision histories of any changes made to any file, element or load module.

(2) CTS-Plus. CTS-Plus is a utility designed to aid in the debugging and testing of simulation programs in both foreground and background environments. It gives the user access to simulation variables and control over module execution, using a simple, yet powerful, command set. Results can be presented in a tabular or graphical format. Newly designed or modified modules can be debugged and tested off-line, then incorporated in the real-time simulation when required.

(3) Performance Monitoring Utility (PFU). PFU provides information about the module execution time and also allows the rearranging of modules in real time. This utility provides the information required for sizing of a new load module when experimental requirements dictate that the software organization must be changed. The utility also provides for substitution of a trial module in real-time without disrupting the experiment.

(c) Aircraft Systems Simulation. Aircraft systems have been simulated to available aircraft data using proven designs. The modules communicate with related modules through a common data base (CDB). The ownship models are high fidelity simulations found on current full flight/mission devices. In addition, the ITEMS package, described below, provides lower fidelity models for a wide range of systems.

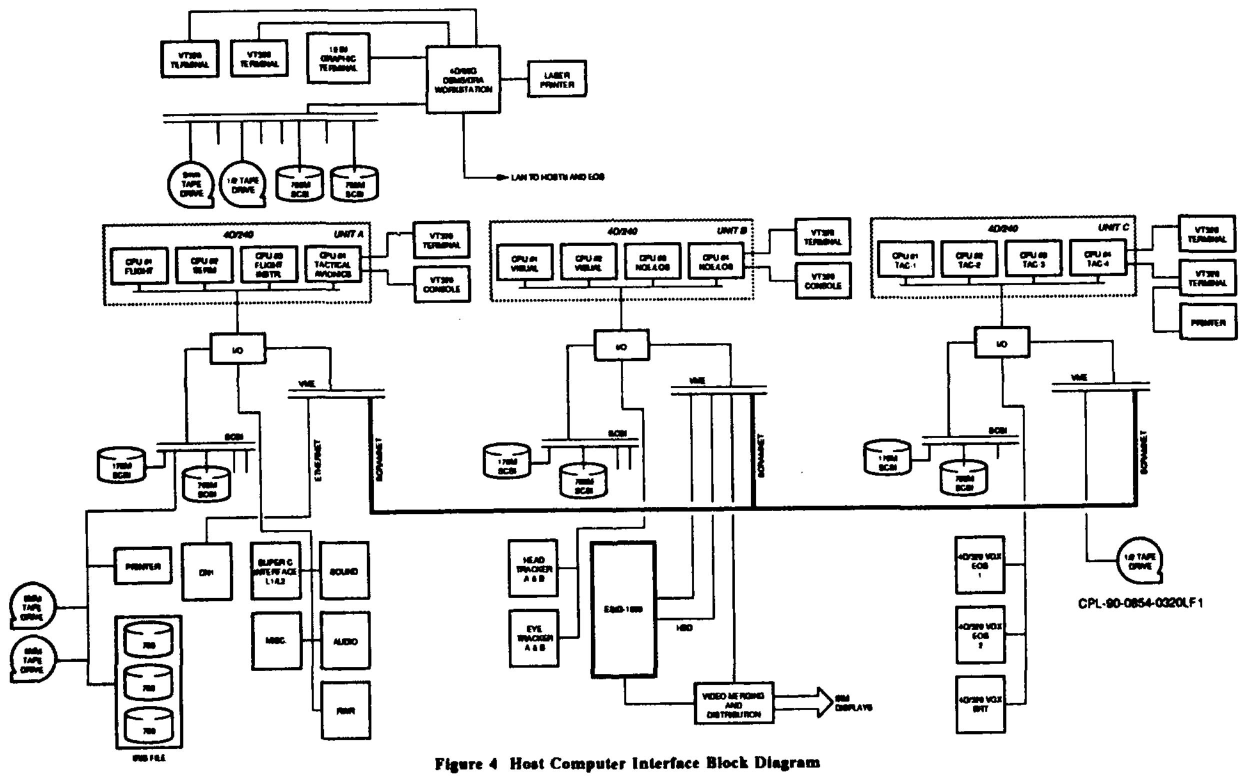

Figure 4 Host Computer Interface Block Diagram

(d) Interactive Tactical Environment Management System (ITEMS). The ITEMS package is the second key software element in providing the reconfigurability required for experimentation. ITEMS consists of the off-line DBMS, which provides the environment for defining players and associated parameters, as well as developing scenarios, and the on-line simulation software which executes and controls the scenario. The ITEMS structure is shown in Figure 5.

(1) Off-line Design. This function is performed on the DBMS workstation. The entire tactical scenario is designed from this station using available data. DBMS provides the tools and editors for the definition of all the tactical elements and is the heart of ITEMS as it controls the level of realism present in the environment that confronts the crew members during any exercise or experiment. The data base hierarchy, shown in Figure 6, provides the user with the capability to define the players in a tactical scenario. There are three general groupings of data bases. The site/systems data base contains all the information required to define any player in the environment. Data for weapons, sensors, vehicle performance parameters, signatures, countermeasures and communication can be input. The tactics data base contains information for manoeuvre trajectories and formations. The manoeuvre trajectories are used to define a path for a player which in real time is evaluated depending on the situations encountered. The player tactics also come into play so that the interaction is as realistic as the defined rules permit. The formations are input so that vehicle formations in multiple vehicle scenarios represent the real world. Formations for all types of simulated vehicles can be accommodated. The rules data base contains information for player doctrine, reallocation and opponent selection. The player doctrine is entered as rules. Rules comprise simple IF-THEN-ELSE constructs that the user enters using a rules editor. The rules are assigned to the appropriate vehicle or system and can be reused as required. The reallocation rules are similar in form to the doctrine rules. These rules are used to determine which players in a scenario are to be active. The reason for this feature is to provide for maximum flexibility when dealing with computer and visual system resources that are usually the limiting factor in the generation of complex tactical environments. The opponent selection rules contain information allowing the player to determine which of the other players in the scenario are adversaries. Data bases are also provided to define weather conditions in the environment. A feature which is not found on previous simulations is wind corridors. The user can define areas of turbulence around features in the data base such as trees, buildings and ship towers. The effect is simulated for both the platform and weapon systems. All the above mentioned data bases are amalgamated, using the scenario editor, into one scenario data base that is run in real time.

(2) On-Line System. The on-line system controls and executes the scenario. The control of the scenario is through the EOS station. In the case of a training device the control would be through the instructor facility. The scenario generally runs automatically with no intervention by the experimenter or instructor, however, any player can be controlled from either the EOS or the BRT stations. The scenario can also be stopped, re-started, resumed or frozen from the EOS. The scenario execution is based on the scenario data base as defined by the user. The data input is used by the simulation modules to provide a realistic environment for the ownship.

(f) Data Recording and Analysis (DRA). The DRA software system consists of three subsystems. First, is the Event Measurement Utility (EMU) which is a background utility; then there are the foreground modules, generated by the EMU, which are used to extract the data in real-time. Finally, there is the analysis package which manipulates the real-time data to provide the necessary reports, diagrams, graphs required for experimental evaluation.

(1) EMU. This is a background utility that allows the user to define the requirements which are then converted to software modules which run in the foreground or real time. The user defines the following:

• CDB Synonyms. These allow the experimenter to redefine variables to be more meaningful in a particular context. This feature is particularly useful where users from various disciplines use different terminology.

• Events. Events are defined using a number of parameters defined as follows:
- event identifier used for data table generation
- event description to more clearly define the event being triggered
- frequency at which the data is collected (sampling rate)
- condition expression, a FORTRAN expression defining an event.

• Measurements. Measurements are defined using a number of parameters defined as follows:

- measurement identifier used for data table generation
- measurement description to more clearly describe what is being measured
- measurement expression, a FORTRAN expression defining what is to be measured in terms of CDB variables.

The experimenter defines these parameters via a user interface tailored for the data types. The output from EMU is the foreground program that contains the necessary information to collect data in real time.

(2) Foreground Synchronous Program. The foreground program consists of two modules. The purpose of the first module is to collect all the relevant CDB variables. This data is then processed by the second module that evaluates event occurrences and calculates and records measurement data for occurring events. The architecture of the host computer is such that the required event and measurement data may be distributed throughout the 12 host CPUs or it could, in certain cases, reside in one CPU. The design of the software provides for all of these possibilities.
The data to be recorded, at this stage, is resident in physical memory of the various units. The task of storing this data is the function of the third element of the DRA system.

(3) Foreground Asynchronous Program. This module resides on the data recording computer which is defined as the unit connected to the output media, the two 8-mm tape drives. Its main function is to write the collected event and measurement data to the tape for later analysis. Other data stored by this program are the mission context data, mission profile data, and control flags that could be important in the analysis of the collected data. The control of the asynchronous program is through the EOS. The DRA pages at the EOS allow the experimenter to monitor and intervene, if required, in the experiment. The system is, however, designed to operate completely automatically. This is an

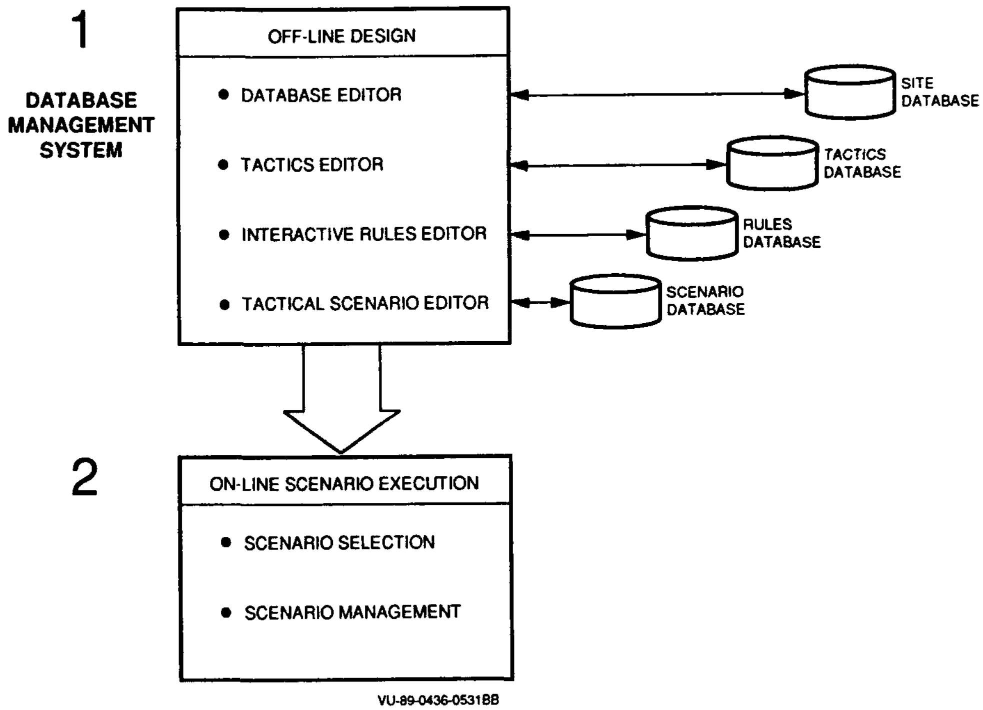

Figure 5 Data Base Management System

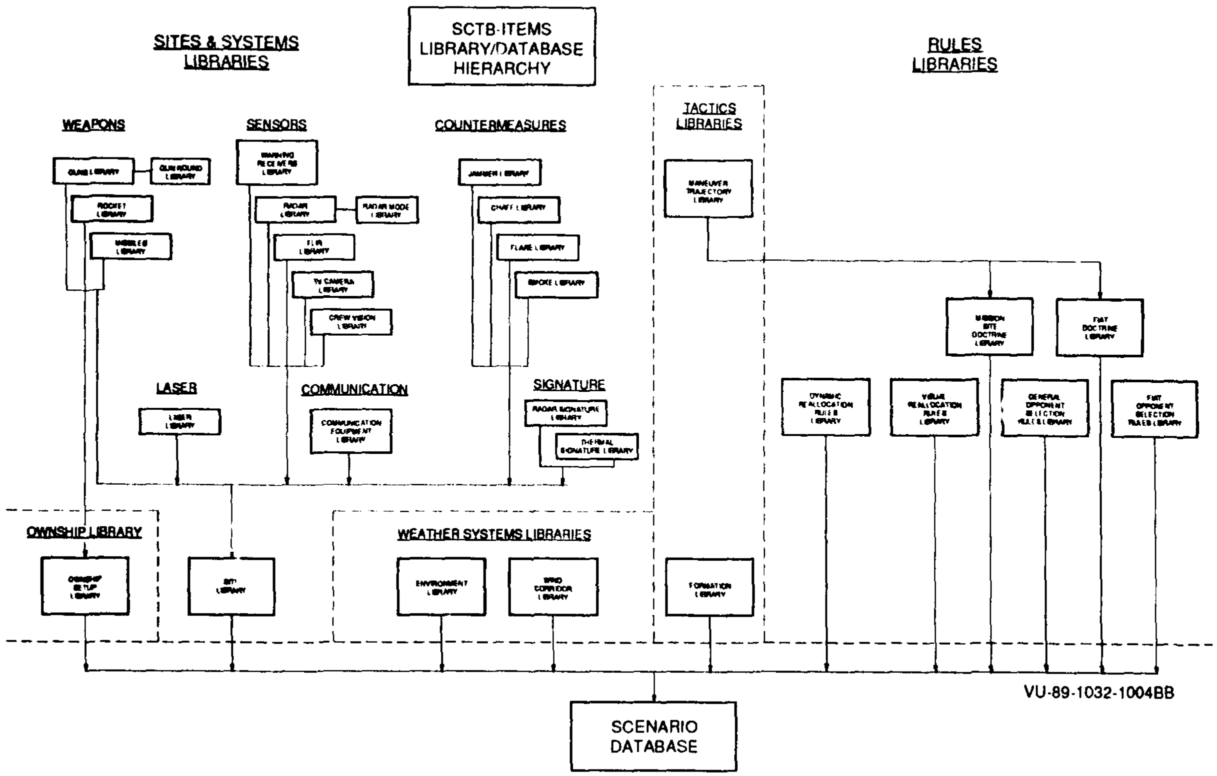

Figure 6 SCTB-ITEMS Library/Data Base Hierarchy

important design feature when an experiment is to be run numerous times with a number of subjects.

4. EXPERIMENTAL USE OF SCTB

The first experiment planned for SCTB will deal with the level of data base scene content in simulator visual image generators. The objectives for this study are to emulate optimum scene content for a low-detail, a medium detail, and a high detail image generation system, assess experienced aviator performance on selected attack helicopter tasks for each scene content/IG emulation condition, and to determine which scene content/IG emulation is required for successful performance of selected Army attack helicopter tasks. The subjects of the experiment will be a group of relatively inexperienced attack helicopter pilots selected using a set of criteria including total flight hours and rank. The pilots will be evaluated while flying scenarios, generated using the ITEMS package, for each of the three IG emulations. The IG data bases will be generated from the existing visual data base using the visual data base modelling station. Optimum budgets for each IG system will be established and maintained throughout each scenario for the four scene content elements. These elements are polygon count, object count, texture maps and colour. The scenario to be run will include tasks selected from the AH-64 flight training categories such as hovering and target identification. It is expected that each pilot will be flying one emulation per day after having an initial briefing the first day. The performance measures will be collected for each one of eight scenario segments. This experiment should yield a matrix of required scene detail for the task segments employed. These results will give insight into the value added by additional scene detail when high detail capable image generators are employed in attack helicopter simulator.

5. FUTURE TRAINING RESEARCH ISSUES

While studying transfer of training effectiveness in flight simulation is the main focus of the SCTB, a number of closely, if not directly, related issues will also be investigated. These investigations shall be focused on providing the Army with training equipment which provide the maximum transfer of training at the lowest cost. The issues are combat skill acquisition and sustainment, hostile environment survivability, emergency manoeuver execution, nap of the earth mission performance, navigational skills, lower hardware procurement costs, visual imagery requirements, scene data base development tools, optimizing instructor operator stations and documentation of training effectiveness. The order in which they are presented is not meant to infer any priority. These are the most relevant issues and each will be addressed in a number of future experiments.

6. SCTB PRODUCTS

The planned products as a result of the research on the SCTB logically follow from the objectives stated above. The following list is not exhaustive but representative:

(a) Functional specifications for a visual simulator to augment primary flight training
(b) Effectiveness of low cost visual technology for advanced training
(c) Modular flight simulator design architecture for the future total training system
(d) Air/land battle simulator fidelity requirements
(e) Multi-simulator networking with other facilities
(f) Data base of empirical data which will be available for other research.

6. CONCLUSION

The SCTB is an advanced research and development facility that has incorporated a number of unique features that have been beneficial to other areas of flight simulation such as commercial flight simulation and nuclear power plant simulation. The hardware and software architecture of the device will allow the Army to build an empirical data base on which effective simulator acquisitions can be made.

G-TOLERANCE AND SPATIAL DISORIENTATION CAN SIMULATION HELP US?

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1. SUMMARY

Pilots of modern fighter aircraft are endangered by high G- forces, loss of situational awareness and spatial disorientation. In order to prepare aircrew for these factors, ground based training facilities simulating some aspects of the relevant phenomena are used. The human centrifuge has proven to be rather effective in increasing G-tolerance, especially in conditions of high onset rate. Unrealistic simulation caused by the small radius of rotation in centrifuges can generate disturbing vestibular stimulation. During the development of the human centrifuge at the Netherlands Aerospace Medical Centre much attention was paid to find methods to suppress these detrimental effects.
Smoothing of centrifuge motion and a realistic, computergenerated outside-vision system proved to be effective measures. Realistic target tracking and a cockpit-like environment are factors which enhance transfer of training.

To simulate the factors which cause spatial disorientation is much more difficult. The complexity of the underlying mechanisms and the restrictions in motion caused by the required rotation to generate G-forces necessitates an extensive research program. Recent developments in orientation training simulators offer opportunities to develop effective training methods to enable pilots to become increasingly aware of and capable of effectively coping with a disorienting task situation.

2. G-TOLERANCE AND SPATIAL DISORIENTATION: CURRENT OPERATIONAL CONCERNS

Over the past decade the numerous losses worldwide of aircrew and aircraft to G-induced loss of consciousness (G-LOC) has deservedly received a high level of attention. In the USAF alone there have been at least 15 pilots lost as well as 19 aircraft, up to May of 1991 [1, 2]. This concern has led to robust programs based on centrifuge training for both inexperienced and experienced fighter pilots [3], and to the development of costly and complex acceleration protection systems [4]. Clearly, the ideal next generation flight simulator should incorporate the capability to provide a realistic biodynamic force environment for pilots engaged in training in air-to-air and air-to-surface operations. This is a capability which cannot be remotely approached in any current flight simulator.

Even more costly than the losses attributed to G-LOC are those associated with Type-I (unrecognized) spatial disorientation. In recent studies by the U.S. Air Force Inspection and Safety Center (AFISC), Norton AFB, CA, spatial disorientation (SD) has been cited as the number one killer of USAF pilots. In these studies, SD accidents have resulted in costs estimated to be as high as US$100 million per year.

Furthermore, these AFISC findings have indicated that loss of situational awareness (LSA) is almost universally associated with these SD accidents. The LSA aspects involved include inexperience, distraction, and

channelization of attention as well as the time perception distortion effects which accompany situations in which a high level of psychological and cognitive stress prevails in the presence of high workload.

The implications deriving from these studies for the design of the next generation flight simulator are clear. First, and most important, the simulator must be capable of generating sustained angular and linear motions sufficient to generate the vestibular effects which contribute to spatial disorientation.

Second, realistic simulation of the mission environment and workload must be provided in order to achieve meaningful channelization of attention, distraction and time perception anomalies combined with the SD effects. This latter consideration defines the requirement, in such a simulator, for high fidelity cockpit simulation and wide field of view colour displays of sufficient detail and resolution to invoke convincingly the mission environment and its demands on the aviator.

For the next generation of flight simulators a new spectrum of human perception and cognition must be addressed if the effects of spatial disorientation and LSA are to be simulated adequately. A thorough understanding of the perceptual/cognitive aspects of the human visuo-vestibular system must be gained through the application of advanced mathematical modelling techniques. Only in this manner will the motion base drive algorithms and aerodynamic models incorporated in the simulators be appropriate to provide the best implementation of flight motion sensation and visuo-vestibular response.

3. NEW MANOEUVRING ENVIRONMENTS

Additional requirements will be imposed on the next generation of flight simulators based upon the oncoming aircraft capability to operate in the "Herbst manoeuvre" post-stall flight regime [5, 6, 7, 8]. It is reasonable to expect that manoeuvres of this type will be used at both high and low speeds. Typical manoeuvres will involve very high angles of attack, approaching 90 degrees, characterized by an abrupt pitch-up motion, followed by yaw around the velocity vector, followed by roll and pitch motions. Manoeuvres of this type will routinely produce compound multi-axis accelerations not now possible in controlled flight. High fidelity simulations of these flight regimes are beyond the reach of conventional six degree of freedom (6DOF) flight simulators with their typically limited travel and inability to produce more than 1G sustained in limited axes and directions.

For research and training there is currently more than one area of deficiency with respect to these flight regimes. No man-rated centrifuge (at least in the Western world) is capable of producing these post-stall regime flight environments with adequate onset rates and multi-axis control. There is already a need for man-rated centrifuges with this capability in order to study issues of support and restraint, controllability at the edge of the envelope, and pre-ejection retraction/restraint in multi-axis acceleration fields. Add to this the requirement for a flight simulator capable of reproducing these environments and it is clear what form the next generation of simulators should take.

4. CURRENT MOTION BASE SYSTEMS

In order to provide a basis for comparison between current flight simulation technology and the type of technology which will be required in the future, it is useful to have an overview of current practice. Table 1 displays a comprehensive survey of the motion base systems which are typical of the current generation of flight simulators. The capabilities available in these systems include the following [10 through 28]:

- Restricted angular motion in X, Y, and Z
- Restricted translational motion in X, Y, and Z
- Heave and sway motions
- Vibration, turbulence and runway roughness simulation
- G-seats and G-suits
- ILS noise simulation
- Limited, wide, and full field-of-view visual systems

Of interest in viewing this matrix is the issue of the importance of restricted translational

motions, heave and sway motions, and vibration/turbulence simulations. These capabilities are seen to be routine in the following types of simulations:

Transport aircraft simulations
Carrier and other non-normal landings
VSTOL low speed operations
Training on primary controls and displays
Pursuit tracking, turbulence, and emergencies
Low altitude/high speed military operations

With regard to transfer of training in air-to-air combat, with and without conventional motion base effects, it has been difficult to show other than negligible differences between the two types of training exposures [9, 10]. In the cases of G- tolerance enhancement in flight simulation and spatial disorientation training in flight simulation the need for motion bases is obvious. The stressors simply cannot be generated without sustained acceleration and angular motion.

In contrast, note that angular motions in pitch and roll appear to be almost universally required across all simulation types and that a requirement for yaw motion is also quite common.
Also sustained acceleration is identified as necessary in military simulations to provide proper cuing [19].

5. THE USE OF CENTRIFUGES AS TRAINING DEVICES

In NATO there are 12 centrifuges in use, of which 8 are used for training of aircrew [20]. These centrifuges are utilised to teach pilots of high performance aircraft to develop the skill of an effective anti-G straining manoeuvre (AGSM). The AGSM is a combination of straining the leg- and abdominal muscles and increasing intrathoracic pressure against a closed glottis.
In order to learn an effective AGSM it is necessary to go through several acceleration profiles in the centrifuge. To prepare the pilots for the G-environment as can be experienced in high performance fighters, high onset rates of G should be generated by the centrifuge. Applying some principles of flight simulation technique showed to be effective in dealing with the consequences of the difference between actual flight motion and centrifuge motion. The main difference between an aircraft and a centrifuge with respect to the generation of G-forces is the radius of turn. An aircraft making a 9 G turn with a speed of 370 knots has an angular velocity of 27 degs/sec. A centrifuge with an arm of 4 m at 9 G has an angular velocity of 270 degs/sec. Any changes in G level in a centrifuge can only be achieved by changes in angular velocity. These changes are sensed by the semicircular canals, as part of the vestibular organs in the middle ear, and can cause severe tumbling sensations. Combined with cross-coupling stimulation of the vestibular organs, by the swing of the gondola, the pilot can be confronted with rather disturbing vestibular sensations which may interfere with the learning process intended by the AGSM training and even cause symptoms of motion sickness.

During the development of the Dutch centrifuge, in cooperation with the Royal Netherlands Air Force and the Netherlands Aerospace Laboratory, several measures were taken in order to counteract these unwanted effects.
In the first place the centrifuge velocity control software was optimized to achieve smooth, jerkfree motion. An F-16 flight-control system was simulated, with a sidestick and a head-up display as control-display elements, to give the pilot full control of the centrifuge motion. On a video monitor in front of the pilot a computer generated outside scene is displayed, representing the attitude of the F-16 with respect to the earth.
A target airplane is displayed. The pilot has to "chase" the target in order to be subjected to the G-profile, needed for the AGSM training. All the profiles are started from an "orbit" of 1.05 G (17 degs of bank). In order to give the pilot the opportunity to anticipate the start of the high onset rate turn and the straining, the target aircraft shows afterburner ignition and a pitch-up, commencing the turn. The target tracking takes some attention and therefore serves to distract the pilot from the vestibular upsets.
These measures are quite effective, as is shown by the fact that, since the Dutch centrifuge came into operation, in only 0.6 percent of the

cases the training had to be aborted because of motion sickness. The Dutch centrifuge is used for training pilots of 8 different NATO countries and several non-NATO countries. The training is rated by the pilots (in an anonymous survey), as very valuable .

Enhanced G-tolerance training effectiveness and fidelity of simulation could be achieved with human centrifuges having multiple, controllable gimbals. Enhanced spatial disorientation training could likewise be achieved with currently available four-degree-of-freedom (4DOF) spatial disorientation simulators with enhanced motion, cockpit and visual simulations. Currently available motion base systems which could be utilized for these applications are briefly described in the following section.

6. CENTRIFUGE-BASED FLIGHT SIMULATION PROBLEMS AND SOLUTIONS

Conventional (6 actuator) motion base flight simulators provide inappropriate motion cues. Because of that their use has been largely abandoned in fighter simulation, as previously noted, though they are still widely used in training air transport aircrews. No positive transfer of training has ever been conclusively demonstrated by the use of the conventional motion base systems in fighter simulations.

It is true that it is impossible for any ground-based simulator to duplicate the six degree of freedom (6DOF) motion environment of an actual aircraft. The principal difficulty in doing so is that curvilinear motion is required to simulate the sustained acceleration environment of real aircraft. These kinds of motion can produce visual/motion mismatches (artifacts) which may hamper the adequate simulation of spatial disorientation and air combat scenarios.

Nevertheless it is necessary to generate sustained angular and linear accelerations in order to provide a relevant spatial disorientation research and training device, and it is necessary to produce high sustained G if human training, performance, and physiology are to be studied in an environment relevant to the air combat arena and other flight simulation scenarios in future generations of fighter-class aircraft.

These motion artifact problems are viewed by the conventional flight simulator design community as the rationale for ignoring centrifuge-based flight simulators. In that community attention has been directed toward a large variety of experimental, invalidated, complex and potentially hazardous techniques in an attempt to overcome the motion base shortcomings of conventional flight simulators [29]. These include G-seats, tissue displacing systems of dowels, lower body negative pressure chambers/suits, goggles simulating the loss of peripheral vision, thermal stimulation of the epidermis, vibratory stimulation, and electro-myographic and electro-neural stimulation.

Early attempts to reduce the effect of the motion artifacts of centrifuges in the operation of dynamic flight simulators have been unsuccessful. The most extensive effort was made at the Naval Air Development Center centrifuge at Warminster, Pennsylvania. This effort involved empirical determination of "transfer functions" of the human vestibular system [30]. The technique was based on subjective inputs from pilot subjects and was never evaluated at high sustained G's. This approach has now been abandoned as ineffective for dynamic flight simulation.

The modern approach to the solution of the motion artifact problem involves the application of engineering "observer" models. These models describe the human visuo-vestibular perception of motion environments. Accordingly the models are capable of predicting the characteristics of any motion environment in terms of the human perception of it.

With this capability it is possible to compare the direction and magnitude of the specific force (the sum of all inertial vectors) with respect to the magnitude and direction of the perceived motion. Through the use of these techniques it is possible to design centrifuge-based spatial disorientation and flight simulation motions so that the environment is optimized in terms of motion perception, and in terms of visual dominance inputs so as to

produce the highest possible fidelity in simulation. This level of fidelity is also enhanced by the inclusion of wide-field-of view, high resolution colour displays and the provision of aircraft-specific cockpit environments.

7. CONCLUDING REMARKS

Ground-based rotating devices like centrifuges are used effectively for training pilots. Recently developed disorientation simulators with fully gimballed and rotating cockpits seem to be capable of the simulation of a wide range of flying manoeuvres, including post-stall and sustained-G flight regimes. This offers the opportunity to attack in a systematic way the problem of disorientation and lack of situational awareness which takes a heavy toll from the military flying community. Much has to be done to solve the problems of motion induced false cuing. Therefore it is necessary to combine the efforts of experts in perception research, flight simulation and aerospace medicine.

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DESCRIPTION	PITCH	ROLL	YAW	X	Y	Z	HEAVE	SWAY	VIB/BUF/TURB	LFOV	WFOV	FULL FOV	G-SEAT	G-SUIT	SUST. G'S	ILS NOISE	RUNWAY ROUGH	
BASIC CONTACT	?	?	?	?	?	?	?	?	?	?	X	X	N	N	N	N	N	
BASIC CONTACT + NAVIGATION	X	X	X	N	N	N	N	N	N	N	X	N	N	N	N	N	N	
FIGHTER MISSION	?	?	?	?	?	?	?	?	?	?	X	X	N	N	N	N	N	
ASUPT R & D									X									
APPROACH / LANDING									X							X	X	
AIR-TO-AIR / AIR-TO-GROUND											X							LFOV for A-G skewed to one side
COMMUNICATIONS, MILITARY	X	X	X						X									
FIGHTER OPERATIONS	X	X	X				X											A 4th degree of freedom not identified.
RAF IP'S & STUDENTS	X	X	X						X									Undefined acceleration effects.
MOST TRAINING	X	X	X															
MILITARY SIMULATIONS															X			Acceleration cues for realism.
ENGINE OUT	X	X	X								X							
FIGHTER (?)	X	X	X															Identified only as a "single seat" simulation.
TRANSPORTS	X	X	N	X	X	X	X	X			X							X,Y,Z all with 24" stroke.
AIR-TO-AIR TRACKING	X	X																
CARRIER & NON-NORMAL LANDINGS	X	X	X	X	X	X	X	X	X		X					X	X	
VSTOL LOW SPEED OPS	X	X	X	X	X	X	X	X	X		X					X	X	
TRAINING ON PRIMARY CONTROLS AND DISPLAYS	X	X	X	X	X	X	X	X	X		X					X	X	
PURSUIT TRACKING, TURBULENCE, EMERGENCIES	X	X	X	X	X	X	X	X	X		X					X	X	
LOW ALTITUDE-HIGH SPEED, MILITARY	X	X	X	X	X	X	X	X	X		X					X	X	
NORMAL OPERATIONS	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?	
GENERAL	X	X					X											
GAT-1 CHEROKEE SIMULATION																		No observed benefit w/motion.
F-4E	X	X	X															Others may have been used.
CARRIER LANDING	X	X					X											

? = NOT FOUND NECESSARY

X = NECESSARY

N = NOT USED OR NOT NECESSARY

BLANK = NOT SPECIFIED

Table 1 Motion and vision as used currently in flight simulators

USE OF SIMULATION IN THE USAF TEST PILOT SCHOOL CURRICULUM

Daniel P. Ringenbach, Test and Evaluation Mission Simulator
Steven E. Louton, NSI Technology Services Corporation
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Air Force Flight Test Center
Edwards AFB, California 93523 USA

SUMMARY

The Test Pilot School (TPS) simulator at the Test and Evaluation Mission Simulator (TEMS) of the Air Force Flight Test Center (AFFTC) is used as an instructional tool which supports USAF TPS instruction in aircraft dynamics and flight control system design. The aircraft dynamics demonstration is given after the students are taught aircraft dynamics in the classroom. In one simulator session each student observes the effects of a change in aerodynamic properties, mass properties and control stick characteristics on aircraft handling qualities and relates the observations to mathematical equations learned in the classroom.

The flight control system design lab uses the simulator as an engineering tool. Student teams analyze, modify, and evaluate a flight control system designs using the simulator by altering the gains, filters, and stick characteristics in real time. Evaluations are based on Cooper-Harper[1] ratings during an air-to-air tracking task and during a landing task. Each team's final solution is flight tested in the Calspan Learjet In-Flight Simulator.

The six degree-of-freedom, real time, TPS simulator at TEMS is an invaluable and versatile tool used by the TPS. It is an effective learning tool providing positive reinforcement of basic aircraft dynamics taught in the classroom and an efficient evaluation tool for flight control systems designed by the students.

LIST OF ABBREVIATIONS AND SYMBOLS

ADI	attitude director indicator
AFFTC	Air Force Flight Test Center
AOA	angle of attack in degrees
Cl_β	variation of rolling moment coefficient with sideslip angle
Cl_{δ_a}	variation of rolling moment coefficient with aileron
Cl_p	variation of rolling moment coefficient with roll rate
Cm_α	variation of pitching moment coefficient with angle of attack
Cm_q	variation of pitching moment coefficient with pitch rate
Cn_β	variation of yawing moment coefficient with sideslip angle
DH	horizontal tail deflection in degrees
HUD	head-up display
I_{xx}	moment of inertia about longitudinal axis
I_{zz}	moment of inertia about vertical axis
N_z	load factor in g's
PSF	pitch stick force in pounds
Q	pitch rate in degrees per second
S/MTD	short take off and landing maneuver technology demonstrator
TEMS	Test and Evaluation Mission Simulator
TPS	Test Pilot School

INTRODUCTION

The Test and Evaluation Mission Simulator's role in the USAF TPS's curriculum is to provide an engineering simulator which can be easily used and modified by TPS instructors and students. In the flying qualities phase of the TPS curriculum, the instructors first use the engineering simulator at TEMS for demonstrating the dynamics of an aircraft such as short period, roll, spiral and Dutch Roll modes. Toward the end of the flying qualities phase of the curriculum, the students come back to the engineering simulator to use it as a tool to ground test a flight control system they have analyzed and modified. This experience shows that the TEMS is effective and efficient in teaching and reinforcing principles of aircraft dynamics and flight control systems evaluations.

TEMS

The TEMS provides a six degree-of-freedom, real time, fixed base, engineering simulator and simulation support to the numerous test programs at the AFFTC. Current simulations at TEMS are the TPS simulator, F-15 S/MTD, B-1B, YA-7F, F-16C/D, and C-17. The facility has the capability to run two simulations at one time using any of four cockpits: F-15, F-16, T-38, and a reconfigurable bomber/transport cab.

Each simulator at TEMS provides an out-the-window visual display based on an IVEX VDS-1000 visual system. The visual display has a color data base of the Edwards Air Force Base local area complete with hangars, roads, dry lakebed runways, control tower, and an F-16 programmable target. Head-up display graphics are programmable and are overlaid on the out-the-window scene. The visual display presents a field of view of 45 degrees in the horizontal plane and 35 degrees in the vertical.

TPS SIMULATOR

Beginning as a simple center stick and attitude director indicator (ADI), the TPS simulator at TEMS has evolved into a fully functioning fixed-base cockpit with full color visual display and head-up display (HUD) graphics.

The aerodynamic model used for the TPS simulator is that of a generic fighter aircraft. The model uses simple tables and linear interpolation to derive the values of 19 basic stability and control derivatives. A multiplier and bias can be added to each derivative by the user, making the aerodynamic model user-definable in real time.

The flight control system model is also user-definable in the longitudinal axis. Gains, filters, and feedback paths can be changed in real time by the simulation operator. The lateral-directional axis uses a simple flight control system with rate and acceleration feedback and is not user-definable.

The stick and rudder pedals are implemented with a McFadden control loader system. With this system force gradients, friction, breakout, and position are adjustable in every axis. The simulator operator can also change a software force gradient and breakout force.

The TPS simulator uses the T-38 cockpit with a video monitor mounted on the front of the cockpit. Cockpit instruments include an ADI, vertical velocity indicator, airspeed and Mach indicators, angle of attack and sideslip indicators, and a normal acceleration indicator.

Two HUD configurations are programmed for the TPS simulator. Figure 1 illustrates a simple HUD used primarily for the aircraft dynamics demonstration. Figure 2 shows the more complex HUD configuration which is used for a landing task with the flight controls project. The simulator operator can select either no HUD or one of the HUDs in Figures 1 and 2 while the simulator is operating.

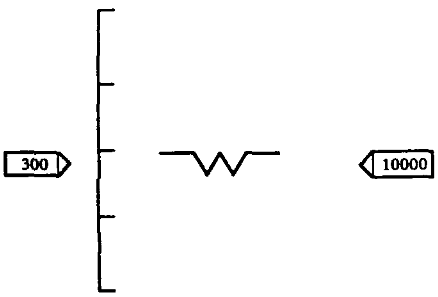

Figure 1. Dynamics Demonstration HUD

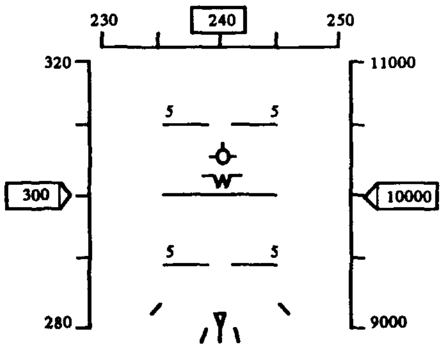

Figure 2. Generic Fighter HUD

The TPS simulator has a pitch tracking task which consists of a target a fixed distance in front of the aircraft that moves up and down in a step or ramp function as programmed by the TPS instructor at the simulator operator's console. Performing a tracking task forces the students to raise their "gain" which makes changes in aircraft dynamics more evident to the student. A landing task is also available which initializes the simulator for an approach to either the main runway or a dry lakebed runway. The landing task can be modified to an offset landing task by initially displacing the aircraft from glide path and course. The offset landing task increases student workload and is better suited to highlight aircraft handling quality deficiencies.

AIRCRAFT DYNAMICS DEMONSTRATION

About one month into the flying qualities phase of the TPS curriculum, the students accomplish a simulator session to augment their academic curriculum in aircraft dynamics. In the classroom, the nonlinear coupled six degree-of-freedom aircraft equations of motion are developed. These equations are linearized and appropriate assumptions are incorporated. Aircraft aerodynamics are analyzed to provide linearized dynamic forces and moments in terms of stability derivatives and aircraft motion variables. This analysis provides students with decoupled linear longitudinal and lateral-directional equations of motion. This, in turn, leads to exploration of the concepts of aircraft dynamic modes such as the longitudinal short period and phugoid modes and the lateral-directional Dutch Roll, roll, and spiral modes.

The TPS simulator at TEMS is used to reinforce these academic concepts and to give a realistic demonstration of how changes in stability derivatives affect open and closed loop aircraft handling qualities. In the simulator session, stability derivatives are first altered to change the natural frequency and damping in the longitudinal axis to show their effect on piloted aircraft handling qualities. Next, lateral-directional derivatives are altered to show their effect on and observe the changes in the lateral-directional modes of the aircraft. Each student is given the opportunity to sit in the cockpit and observe the changes in longitudinal and lateral-directional modes of the aircraft.

Longitudinal Dynamics

For the longitudinal dynamics demonstration, the longitudinal axis is isolated by changing the TPS simulator to a three degree-of-freedom simulation. The students are shown how the stability derivatives Cm_α and Cm_q and the aircraft mass properties are analogous to the spring-mass-damper system as shown in Figure 3.

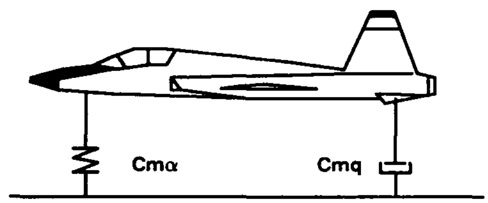

Figure 3. Spring-Mass-Damper System

Each student is then given the three longitudinal dynamic cases shown in Table 1. From the operator's console, the TPS instructor changes the bias on Cm_α and Cm_q to obtain the desired short period natural frequency and damping ratio. In each case, the student performs a pitch doublet to excite the short period, and views the results of the input on the visual display and on strip chart recorders. The student also performs a closed loop pitch tracking task to qualitatively evaluate gross acquisition and fine tracking. For this closed loop task, a target is placed in front of the aircraft and the HUD in Figure 1 is used. The student attempts to place the waterline marker on the target as it moves in an unpredictable path of ramps and steps in the vertical axis.

For the first case, a bias is added to the baseline values of Cm_α and Cm_q providing an aircraft with a low natural frequency and low damping ratio. Performing an open loop pitch doublet, the students note the sluggish pitch response and the attitude overshoots that occur with this configuration. Performing a closed loop tracking task, students comment on the poor gross acquisition and fine tracking capabilities of this configuration.

Table 1. Longitudinal Dynamics Cases

CASE	Cm_α Bias	Cm_q Bias	Damping Ratio	Frequency	Expected Results OPEN LOOP	CLOSED LOOP
1	-0.075	+1.25	0.13	1.16	low frequency low damping	slow response poor gross acquisition poor fine tracking
2	-1.346	-5.00	0.13	6.60	high frequency low damping	fast response good gross acquisition poor fine tracking
3	-1.346	-40.0	0.80	6.60	high frequency high damping	quick response good gross acquisition good fine tracking

For the second case, the instructor increases the bias added to Cm_α and effectively moves the center of gravity forward. The value of Cm_q is modified to maintain a constant damping ratio. With the increased natural frequency, the aircraft initial response to the open loop doublet is quicker, but pitch attitude overshoots remain. These dynamics are reflected in the closed loop tracking task by comments indicating improved gross acquisition capabilities with continued poor fine tracking results. The students are unable to aggressively track the target aircraft without excessive pilot compensation to overcome aircraft deficiencies.

The third case maintains the same natural frequency, but increases the damping ratio. The open loop doublet shows a continued quick initial time response with a significant reduction in pitch attitude overshoots. The closed loop tracking task reflects an improved fine tracking capability while maintaining good gross acquisition response.

To demonstrate the effect of control stick dynamics on the aircraft handling quality evaluations, the instructor varies control stick characteristics such as breakout and force gradients and elicits student comments. This procedure is extremely effective in convincing students of the importance of achieving a proper harmony between aircraft dynamics and control stick dynamics.

Lateral-Directional Dynamics

For the lateral-directional demonstration, the lateral-directional axes are restored and the pitch axis is damped as in Case 3 of the longitudinal demonstration so as to not interfere with roll stick inputs. This demonstration alters stability derivatives Cl_p, roll damping, and $Cl\delta_a$, aileron power and shows the effect of these derivatives on roll response characteristics. The stability derivatives effect on the Dutch Roll and spiral mode characteristics are also shown by altering the derivatives Cl_β and Cn_β.

For the roll response demonstration, the student initiates a bank angle capture task by rolling 45 degrees to the left, and then attempts to aggressively achieve a 45-degree right roll angle. This is done for each of the four individual cases shown in Table 2. In each case the student evaluates the aircraft response in terms of roll response and ability to capture a desired roll angle.

The first case gives the aircraft low roll damping and low aileron power. When the student initiates a roll command, the roll response of the aircraft is very sluggish due to effectively small ailerons. Trying to stop the aircraft at a desired roll angle is also very difficult because of the low roll damping.

Increasing the roll damping by adding a bias to Cl_p in the next case shows the aircraft can be easily stopped at any angle and will not overshoot. However, the low aileron power makes the roll response slow.

Leaving the the bias to Cl_p, effective aileron power is increased by adding a bias to $Cl\delta_a$. The aircraft now responds quickly to roll inputs and stops but does not go past the desired bank angle.

Table 2. Roll Response Dynamic Cases

CASE	Cl_p Bias	Cl_{δ_a} Bias	I_{xx} Multiplier	OPEN LOOP EXPECTED RESULTS
1	0.0	0.0	1.0	low roll damping, low aileron power
2	-1.5	0.0	1.0	good roll damping, low aileron power
3	-1.5	-0.007	1.0	good roll damping, good aileron power
4	-1.5	-0.007	5.0	high inertia, difficult to start and stop roll

Finally, with a responsive and controllable aircraft, the inertia of the aircraft is increased to that of a large aircraft. In this case, the effects of aircraft inertia are exaggerated and the aircraft resists rolling when there is a roll command input, and has difficulty capturing a bank angle or precisely stopping a roll after it has started.

After the roll response demonstration, the aircraft is returned to its normal dynamics to demonstrate the three cases of different Dutch Roll and spiral mode characteristics shown in Table 3. In each case the student first performs a rudder doublet to excite the Dutch Roll mode and after that, banks the aircraft to examine the spiral mode stability. The first case adds a bias to Cn_β which causes the Dutch Roll mode to have a predominate motion in the yaw axis and causes an unstable spiral mode. Making Cl_β more negative by adding the bias shown in Case 2 makes the Dutch Roll mode have a predominate rolling motion and makes the spiral mode stable. Lastly, the inertia term, Izz, is altered to illustrate its effect on the Dutch Roll mode.

Effectiveness of the Demonstration

The TPS simulator at TEMS gives the instructors a time-efficient teaching tool for reinforcing basic aircraft dynamics concepts. The simulation software and operator's console are easy to use and flexible so that the TPS instructor can easily step through the demonstration without the help of a simulator operator. In a short period of time, a TPS student can experience the effects of changes in aircraft stability derivatives and inertias on aircraft handling qualities by flying rather than by watching. Ground simulation is effective because students obtain tangible, hands-on experience with variable aircraft dynamics and flying qualities which cannot be equally demonstrated through classroom instruction. The TPS continues this academic reinforcement by providing variable stability dynamics sorties using the Calspan Learjet. Use of ground simulation makes each sortie more productive because the students know what to expect during the sortie.

Table 3. Dutch Roll and Spiral Mode Dynamics Cases

CASE	Cn_β Bias	Cl_β Bias	I_{zz} Multiplier	OPEN LOOP EXPECTED RESULTS
1	+0.3	0.0	1.0	yawing Dutch Roll mode, unstable spiral mode
2	0.0	-0.2	1.0	rolling Dutch Roll mode, stable spiral mode
3	0.0	-0.2	0.1	rolling Dutch Roll mode, stable spiral mode low rolling inertia

FLIGHT CONTROL SYSTEM PROJECT

Toward the end of the Flying Qualities phase of the TPS curriculum, the students are given a flight control system project. This project involves analyzing a longitudinal axis flight control system with marginally acceptable handling qualities and modifying both the control system and the control stick dynamics to produce an aircraft model with better handling qualities. To simplify the task, only the longitudinal axis is analyzed and only one flight condition, power approach, is tested. The purpose of the project is to not only teach the students about flight control systems but also to teach them the process used to test a control system. This iterative process is shown in Figure 4.

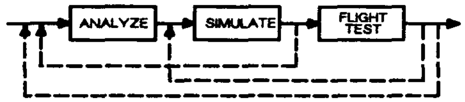

Figure 4. Test Process

A simplified diagram of the simulator pitch flight control system is shown in Figure 5. This flight control system is simple to understand and analyze, yet sufficiently challenging to make the student realize the complexity of digital flight control systems and the difficulty involved in designing and analyzing these systems.

Using control system analysis software on a personal computer, student groups of pilots, navigators, and engineers first analyze the original design and then come up with alternative designs by modifying the filters and selecting appropriate gains for the pitch rate, angle-of-attack, and normal acceleration feedback paths.

With several possible designs on paper, student groups are scheduled on the TPS simulator to put their changes in the control system and fly them. The TPS simulator is very flexible and the control system can be changed by the students in real time at the operator's console. The student can change gains in any path, change filter coefficients, and change the stick gradient and breakout. The students are advised not to simply change gains and see what happens, but are required to develop a simulator test plan and methodically step through their possible solutions. Pilots in the group fly each design and assign each a handling qualities rating based on the Cooper–Harper Pilot Opinion Rating Scale while engineers and navigators run the simulator tests, write down pilot comments, and assemble the data collected. After the simulator session, the students analyze the results of their tests and then come back to the simulator to check their final design.

Once the design is complete and the students are satisfied with their results, they present their design to the Calspan Learjet engineer who sets the in-flight simulator to fly their design. When all of the groups have their designs, every pilot in the class qualitatively evaluates each group's best flight control system design in the Learjet, and an overall best design is chosen after assessing all pilot comments.

Effectiveness of the Project

The use of the TPS simulator at TEMS is effective for the flight controls project for a number of reasons. First, the simulator gives the students the opportunity to evaluate their theoretical solutions before having to test them in the in–flight simulator. It allows the students to experiment with several different solutions and choose the best one. Second, the engineering simulator is taught as part of the flight test process which is to analyze, ground test, and flight test the system. The flight controls project places an emphasis on using ground simulation before flight test and, in the future, the TPS students will know that ground simulation testing before flight testing is a safe way to efficiently flight test a system. Third, the ground simulation makes flight test of the groups' designs in the Learjet more productive. Lastly, the simulator is judged to be an effective tool for the flight controls project by favorable responses given by the students in questionnaires given to them after completion of the project.

CONCLUSION

The TPS simulator at TEMS is indeed an effective engineering and instructional tool in the curriculum of the USAF Test Pilot School. The dynamic demonstrations in the longitudinal and lateral–directional axes give a TPS student a visual representation of the effect of changing stability derivatives

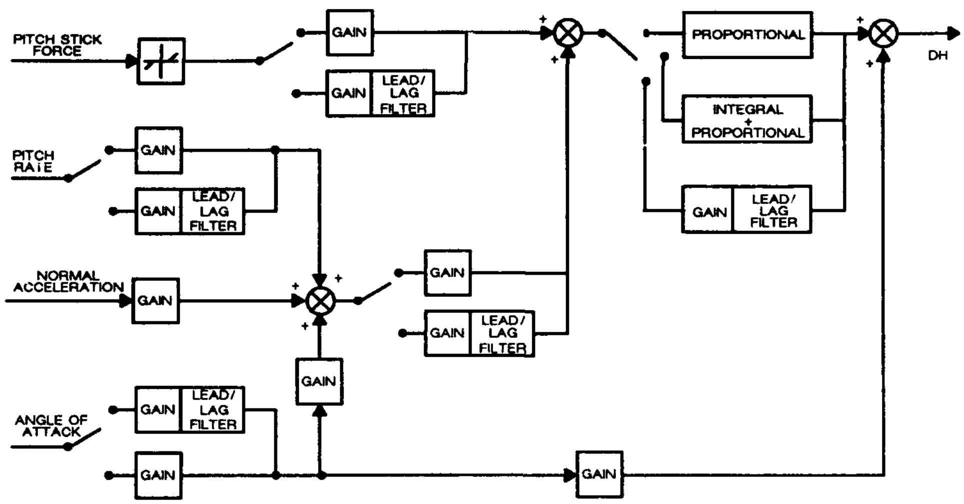

Figure 5. TPS Pitch Axis Flight Control System

on the short period in the longitudinal axis and on the roll response, Dutch Roll mode, and spiral mode in the lateral–directional axis. The hands–on experience of the TPS simulator provides a positive reinforcement of the academic concepts learned in the classroom.

The simulator also proves to be an effective tool for the flight control system project. It provides the student groups with feedback on their control system designs and with output data which can be used to revise and improve their original design. By giving feedback during the design phase of the project, the students learn more about flight control system analysis and design and finish the project with a better design and a much deeper understanding of flight control systems.

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AM-X Flight Simulator from Engineering Tool to Training Device

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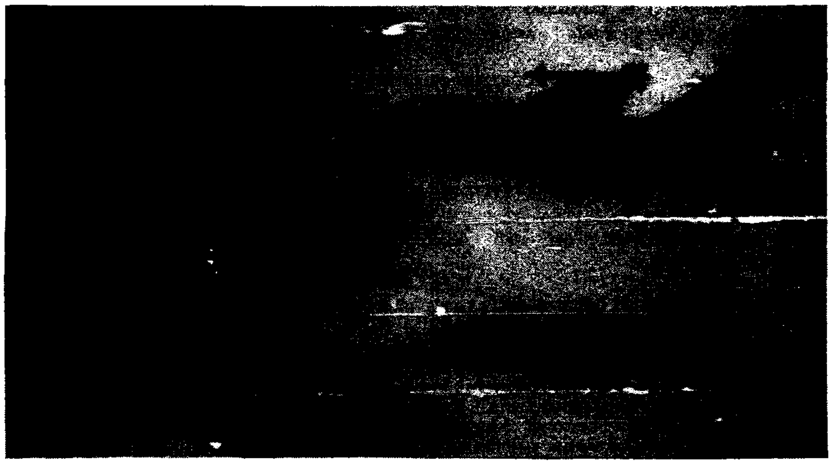


1. Introduction

Effectiveness of Flight Simulation with pilot-in-the-loop can be intended rather differently depending on the context in which the simulation activities are carried out, namely in the two traditional areas of Research & Development (R&D) and Training.

In the latter case effectiveness can be considered the amount of training a simulator is able to transfer per time unit, whilst in the case of R&D simulation its effectiveness is related to the amount of confidence engineers can gain in the prediction of an airborne system behaviour before releasing it to the real flight.

Pursuing the maximization of effectiveness in these two different contexts leads usually to different approaches in applying simulation methodologies.

This paper will show to what extent a simulation facility created and continuously improved to support the development of a new attack aircraft, the AM-X, was finally capable of training operational pilots during the conversion to that aircraft.

In a former AGARD FMP Symposium on Flight Simulation in Cambridge (ref. 1) a paper was presented with the purpose of showing which results had been obtained using a simple and economic simulator configuration.

At that time flight test activity was performed with some prototype aircraft: today, while the last planes of the second production batch are being delivered and FOC shall be released by the end of the year, flight test is undergoing for the two seater version and for the new avionic/armament configuration of the third production batch.

Therefore the main activities and improvements performed in this period of time, that include both R&D and training, will be illustrated in the following.

2. The first configuration of the AM-X Flight Simulator

At the beginning of the AM-X programme flight simulation facilities in Aeritalia were those used in the development of previous aircraft, and in particular the G 222 and Tornado. These facilities included a visual system based on a moving belt and a colour TV camera, allowing 6 degrees of freedom (DOF) but with severe limitations.

A fixed-base preliminary cockpit was installed in an inflated dome, used at

that time as a screen to project external world view derived from the moving belt only in the sector in front of the cockpit.

This basic configuration presented evident limitations, requiring a considerable amount of accommodation to the test pilots involved in the simulation activities. This notwithstanding, it was possible to complete in a satisfactory manner several important tasks in the early development programme, and namely:

- sizing of the flight control system;
- dampers gain and authority optimization;
- take-off and landing performance optimization including ground effect;
- high lift devices transients study and compensation;
- optimization of cockpit layout and Hands On Throttle And Stick (HOTAS) philosophy;
- preliminary definition of HUD nav/attack formats.

The arrangement of the flight simulator, as said, was such that the test pilots involved in the evaluations were forced to adapt themselves to the situation and to use their imagination in correctly interpreting "rough" informations and cues. However, well experienced company and Air Force test pilots were perfectly able to satisfactorily perform the required activities, giving the engineers enough data to complete the planned activities and project further developments.

On the contrary, trainee pilots should not have gained very much from such a simulator configuration.

To overcome mainly the limits of angular and linear displacement and velocities of the above mentioned system, the simulator configuration was subsequently updated to include a simple but effective external world image generated by a general purpose graphic computer. This image was free from space-time limitations, allowing to carry out any kind of flight manoeuvres. A sleewable area of interest projector allowed to display to the pilot the object considered the most important for the specific task (namely an airfield or another aircraft), also when it was outside the sector in front of the cockpit.

In addition, to give the pilot a feedback of attitude also when looking at the slewed image outside the front sector, a basic two-axis sky-earth projector was installed in the dome.

With this upgraded configuration it was possible to perform some interesting tasks like specific investigation of handling qualities during in-flight refuelling or formation flight, air target tracking with gunsight and particular profiles of air-to-ground attacks like pop-up manoeuvres, high angle bombing or jerking during attack both for handling qualities assessment and human factors evaluation.

3. The improved configuration

The next activities in the AM-X development programme requiring flight simulation support were the investigation of handling qualities and definition of the authorized flight envelope in the degraded all mechanical back-up FCS mode following a double hydraulic failure. In this mode the pilot feels the loads induced on the stick by the hinge moments directly.

Some simulations of specific situations had been already performed with the previous simulator configuration (e.g. flame out patterns), simulating stick forces corresponding to a typical flight condition with the use of adequate springs and frictions. However, to carry out a more detailed assessment it has been necessary to acquire and integrate in the simulator a digital Control Loading System (CLS).

Using this CLS all required tests were performed, resulting in the demonstration of the adequacy of the manual mechanical back-up mode in controlling the aircraft in the vast majority of flight conditions. However, in some particular conditions (e.g. if the double hydraulic failure occurs during sustained manoeuvres at low altitude or during landing with rough air), the aircraft controllability could be critically reduced. From these results a decision was taken to introduce in the aircraft hydraulic system two accumulators serving the pitch and roll axis controls, enabling a great number of manoeuvres. Of these two accumulators, one acts automatically at the moment of pressure drop to enable a recovery action with powered controls, while the other is put under pilot control in order to be selected prior to the final landing.

This CLS was installed in a new cockpit, better representing the production standard aircraft, equipped with aircraft standard displays and controls such as HUD, Navigation Data Entry (NDE) facility and Weapon Control Panel (WCP) (fig. 1), mainly for the purpose of evaluating the nav/attack system from an operational point of view.

Emulating the aircraft MIL-STD-1553B databus was also necessary, together with simulating the aircraft sensors and some weapons.

At the same time, to evaluate operational concepts of a real mission it was required a better visual system than the basic one in use, in order to overcome limitations of the flat and schematic terrain data base used at that time.

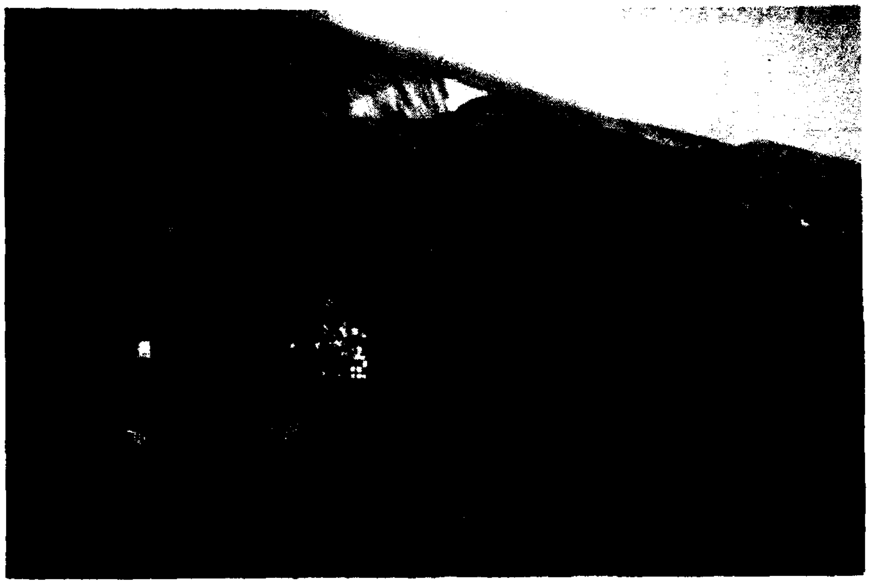


FIG. 1

For these reasons the acquisition of a General Electric Compuscene IV CGI system was decided, despite its high cost. A three windows visual configuration was adopted, projecting inside the dome an image covering a FOV about 160 deg. in azimuth by 45 deg. in elevation, that had been considered sufficient for most A/G tasks and adequate enough for supplying the pilot with cues for any possible manoeuvrability and controllability assessment (fig. 1).

The availability of such a system was the great lap in simulation realism, allowing realistic and effective simulations of low altitude nav/attack operations, formation flights, in-flight refuelling and some assessment of air-to-air defensive capabilities.

However, the two most important activities with the new flight simulator configuration were the high angle of attack and spin evaluation and the validation of the nav/attack system.

4. High Angle of Attack and Spin Simulation

The high angle of attack, departure and spin behaviour evaluation was a programme jointly performed by Aeritalia and Aermacchi engineering departments, in a first phase on the AM-X flight simulator and later on in parallel at the flight test range in Sardinia.

High angle of attack flight testing was considered a fundamental step in the development of AM-X. In order to be adequately prepared prior to flight testing activities, which are potentially highly demanding and often risky, the AM-X flight simulator was extensively used in a significant number of activities, whose goals where primarily:

- evaluation of handling qualities close to stall, at stall and beyond stall;
- determination of resistance to departure/spin;
- search for a simple and effective recovery technique;
- identification of the operational and safety limits.

The aircraft configurations for these tests included (Fig. 2):

- clean aircraft;
- high wing inertia;
- asymmetric under-wing stores;
- underfuselage stores.

Aerodynamic tests were carried out in the subsonic wind tunnel at Aermacchi. Using both rotary and fixed balances permitted the evaluation of aircraft behaviour at stall, the control effectiveness and the aerodynamic impact of the external stores.

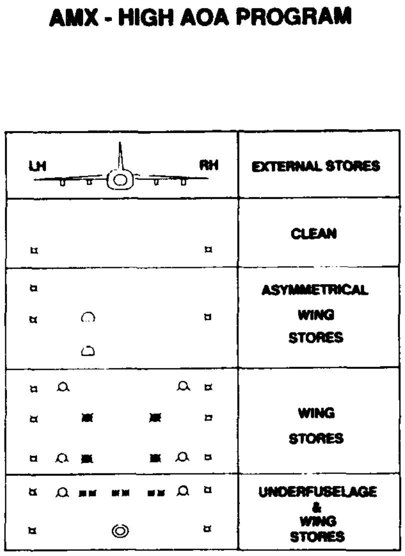


FIG. 2

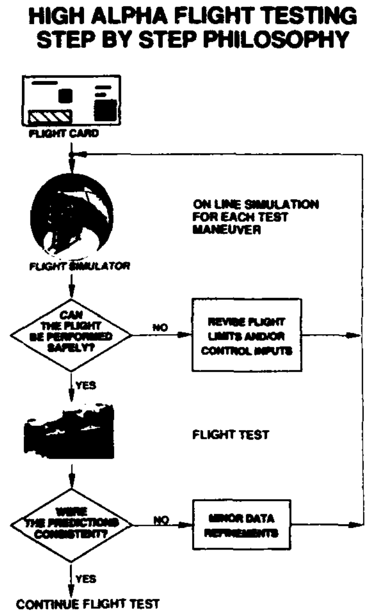


FIG. 3

The tests in the vertical wind tunnel were performed at the I.M.F.L. (Institue of fluid Mechanics of Lille, France), and were of paramount importance for the initial prediction of aircraft behaviour during fully developed spin, both erect and inverted. All these studies allowed the implementation of an aerodynamic data set up to 90 deg angle of attack and 40 deg sideslip.

The entire flight envelope envisaged for the high incidence tests was then explored through flight simulation.

The following approach was adopted: first the manoeuvres foreseen for each specific test flight were performed on the simulator by an AM-X programme test pilot, assisted by a team of flight mechanics, aerodynamic and flight test specialists supported by the simulation specialists. Based on these simulation tests, predictions of analytical models were confirmed and the decision to proceed in flight test activities was then taken with a good confidence of ensuring the adequate safety levels (Fig. 3).

Flight tests results in effect confirmed the representativeness of the simulation evaluations and the correctness of the predictions made (Fig. 4).

The results of the whole activity were the confidence that the single seater aircraft is completely safe with respect to roll departure at high angles of attack and to accidental spin, and commanded spins can be easily recovered using conventional techniques also in case of asymmetric external stores configurations.

It can therefore be stated that the availability of suitable simulation tools proved essential to the achievement of the objectives of the AM-X high alpha flight test programme.

5. Nav/attack System Validation

For the validation of the AM-X nav/attack system, as said before, aircraft standard hardware has been deemed necessary, so a certain number of equipments, mainly of the displays and control subsystem, has been acquired and installed in the simulator cockpit.

The availability of such an avionic configuration allowed to carry out effective evaluations in two main areas: avionic system moding and aiming stability (Fig. 6).

Nav/attack moding functions and weapon aiming algorithms are on the AM-X implemented in the main computer: these have been emulated on the simulator computers, connected to cockpit displays and controls via the real avionic bus.

This solution allowed easy software changes in the simulated main computer, as derived from comments collected from test pilots during the assessments on the simulator.

AMX - ROLLING DEPARTURE

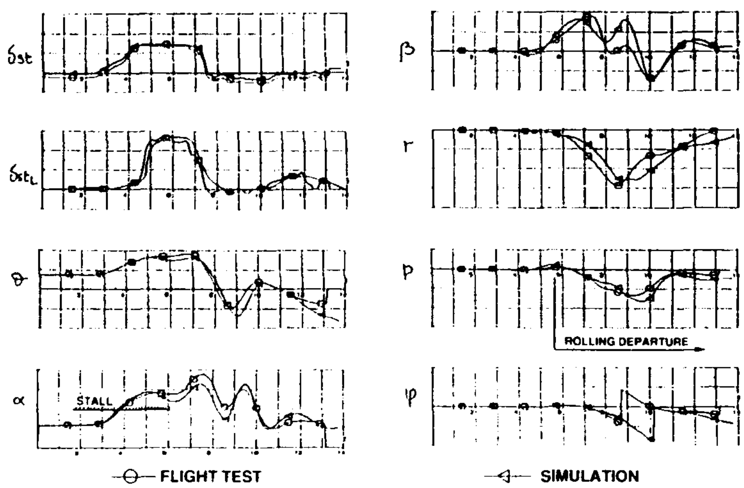
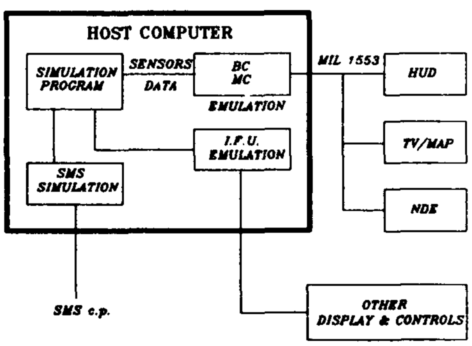


FIG. 4

AMX FLIGHT SIMULATION AVIONICS



In fact, since the basic AM-X aircraft is a single pilot, low altitude attack aircraft able of carrying a large variety of weapons requiring different acquisition, aiming and delivery tactics and techniques, the moding and ergonomy must be carefully considered and integrated with the weapon system capabilities and limitations.

So it became clear that a realistic simulation of the operational mission or at least of its critical phases was the only way to understand how to achieve such an optimization.

Among the different areas in which the AM-X flight simulator has been used for the above mentioned purpose, some peculiar examples are investigation on weapon aiming symbols presentation, Flight Director and Autopilot development and HUD formats and symbologies definition.

6. Weapon Aiming

On the side of weapon aiming stability, the simulator supplied a useful support both in A/G and A/A tasks.

In the A/A gun mode the preliminary assessments on the flight simulator had led to the definition of some time constants in the smoothing filters, mainly oriented to ease the pilot in superimposing the aiming symbol on the HUD onto the target (Fig. 5).

At the end of this first activity target tracking was a very simple task both in the simulator and in flight "dry" attacks. However, when we went to the gunnery range, results in terms of accuracy where a different matter. In fact, in the continuous tracking mode there was no way to put the bullets inside the towed drogue unless the HUD aiming symbol was stabilized on the target for about 4 seconds.

This was definitely considered unacceptable and a new study and new simulation tests where necessary. The problem derived from factors like the combination of a series of filters with the radar rangefinder sampling intervals and algorithm extrapolations.

A rather similar problem was found in A/G bombing: in this case it appeared in the opposite way. In fact, preliminary assessments on the flight simulator of the Continuously Computed Impact Point (CCIP) (Fig. 6) mode has been made considering ideal conditions (such as flat terrain, continuous and perfect radar ranging returns), this leading to the choice of not introducing any smoothing filters in the HUD symbology drive.

In fact, early flight tests results indicated presence of some critical, unacceptable oscillations in elevation of the HUD weapon aiming symbology during attack manoeuvres.

In both A/A and A/G referred cases the problem was substantially the same: smoothing heavily the HUD symbology would result in easy handling and tracking but only steady state conditions would guarantee the required accuracy. An analytical approach accounting for all the involved variables, including dynamic aircraft response, should have required an effort judged impractical and incompatible with the programme time schedule. So a more empirical approach involving the extensive use of the flight simulator was chosen.

In a few days a simplified model of the main characteristics of the sensors behaviour was implemented in the simulator and a method for the evaluation of the aiming error was prepared: during either A/G and A/A tracking manoeuvres performed in a realistic way against ground or air targets, all the simulation was frozen by the pilot fire signal and the HUD aiming symbol angular position was recorded and displayed to the operator. Then the aiming algorithm was run with all input frozen until all the filters had reached a steady state condition and the final HUD aiming symbol position was considered to be the

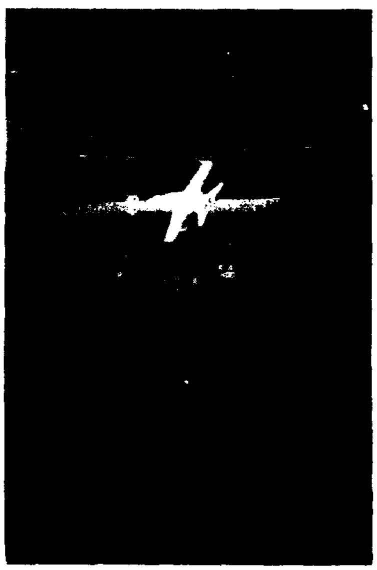


FIG. 5

FIG. 6

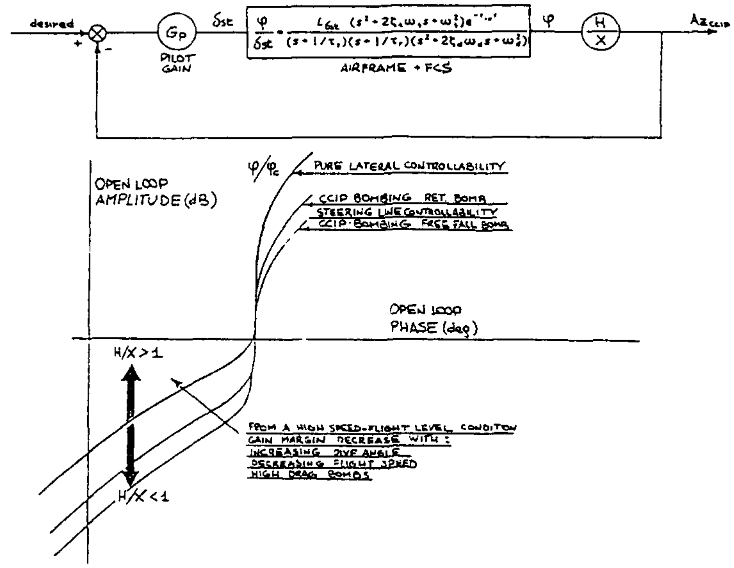


FIG. 7 - AM-X CCIP steering line controllability

most accurate achievable for that algorithm: the difference between the two positions was the aiming error due to the dynamics of the attack.

The work now was only to perform several attacks with experienced engineers changing the values of time constants and measuring the accuracy in the simulator control room, while the pilots performing the attacks were able to rate the handling qualities of the HUD aiming symbol for the tracking task.

When a point was reached in which accuracy and pilot disappointment where acceptable, the corresponding set of time constants in the filters was considered suitable.

Flight tests now undergoing with these values, even if not yet completed, show satisfactory improvements.

Another problem was the lateral controllability of the HUD aiming symbol pilots were complaining about when aiming high drag ordnance.

In this case the flight simulator proved useful for the engineers to identify the problem, but nothing was changed unless the delivery procedure, that in turn was verified on the flight simulator.

The problem has been discussed in detail in the paper "Flying Qualities Experience on the AM-X Aircraft" (ref. 2) presented at a former AGARD symposium by Alenia handling qualities engineers.

Under specific circumstances, pilots found very difficult to stabilize the HUD steering line in the CCIP mode over the target. It was identified that this difficulty was increasing with the increasing of the altitude to throw ratio. This H/X ratio depends on the ballistic of the bomb and on current flight conditions (Fig. 7).

The analytical study showed that as the ratio approaches 1.0 the aiming task appears to the pilot as easy as the lateral control task. In case of low speed, high dive angle or for delayed bombs (i.e. H/X > 1), the frequency response curve moves toward the closed loop resonance area and lateral PIO conditions are achieved.

On the basis of the above consideration on the diagram of Fig. 8 the line H/X = 1.0 reflects the conditions for which the weapon aiming task is very similar to the aircraft lateral controllability. The area standing on the right side of the line H/X = 1.0 indicates conditions of an easy task, whereas proceeding on the left side a more and more difficult task and even PIO occurrence are to be expected. The only way to avoid this problem is to fly trajectories that keep the H/X ratio sufficiently low.

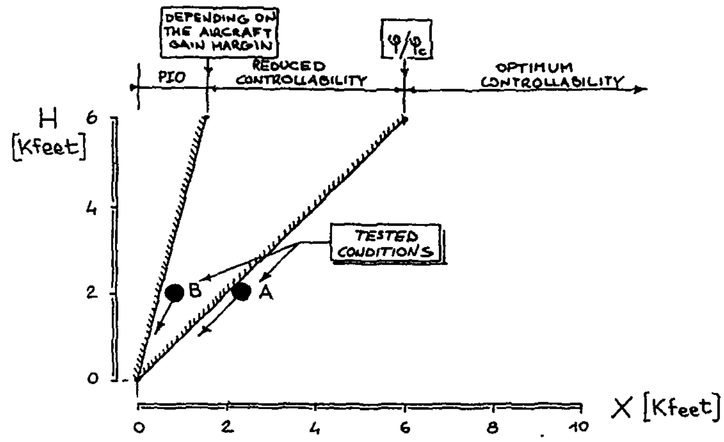


FIG. 8 - Limits on altitude delivery H versus downrange distance X for good CCIP steering line controllability

7. Flight Director and Autopilot Development

In the AM-X programme workshare, the responsibility of developing the FD was assigned to Embraer, but since the Alenia AM-X flight simulator is the only one available, it has been used also for all tests required in the development of this system, with the participation of Embraer engineers and test pilots.

Simulation activity not only included assessment of A/P and FD control laws in all modes, including VOR/TACAN simulation accounting for indetermination zones and radio signal disturbances, but also allowed verification of moding of these systems. To achieve this goal, FD and A/P controls and displays in the cockpit have been built in house and used to verify their adequacy prior to commit production of the real aircraft hardware.

A specific case in which the simulator proved essential was the evaluation of the A/P Control Steering function. The basic A/P design included a control on the stick top, operated by the pilot hand palm on grabbing the stick, to momentarily disengage the currently engaged A/P mode. With this facility the pilot was able to override A/P, re-engaging it at the moment of leaving the stick.

Preliminary tests have indicated no problems, until during a simulation session the pilot, accidentally, first moved the stick without acting on the palm control, then operated it. In fact, this resulted in an abrupt manoeuvre that led the (simulated) aircraft to lose control and almost hit the ground!

Subsequent analysis allowed to locate the problem in the fact that stick displacement when an A/P mode is engaged, due to the mechanical back-up flight controls system, results in input to the control surfaces that are contrasted by the A/P commands. If in this competitive situation A/P is then disengaged by the pilot hand control, although an appropriate fader have been included, potentially dangerous situations were still possible.

Alternative designs were then considered, and new simulation assessments performed. Finally, a compromise solution satisfying both safety and pilots ergonomic requirements was developed introducing a software threshold in the longitudinal and lateral flight control channels, surpassing which automatically disengages A/P mode with positive indication to the pilot.

The flight simulator was then used for calibrating this threshold and to develop adequate fader function to revert from A/P to piloted control in a smooth and safe way.

8. HUD Formats and Symbology Development

AM-X is the first aircraft equipped with an HUD completely developed in Italy. This meant not only developing the hardware suited for being installed in the AM-X and capable to exploit the good external visibility of the aircraft, but also specifying the formats and symbols tailored for the AM-X missions.

After the use of the simulator in supporting flight mechanics studies, this activity was probably the major application of the flight simulator in the AM-X programme. As for the handling qualities, the human "loop closure" is so essential for this activity that hardly you could obtain meaningful results without using a flight simulator. This is mainly because, as the primary information source for the pilot, the HUD connects him directly to the external world, matching his cognitive perception to his short term decision process with extraordinary effectiveness that can not be predicted on analytical basis.

For the AM-X this process took place in two steps. The first one was performed using the initial simulator configuration, with a home build HUD connected to a commercial graphic computer. This produced a set of formats and symbologies that was implemented and flown on the avionic prototypes and then, with minor modifications, introduced on the first two production batches of the AM-X.

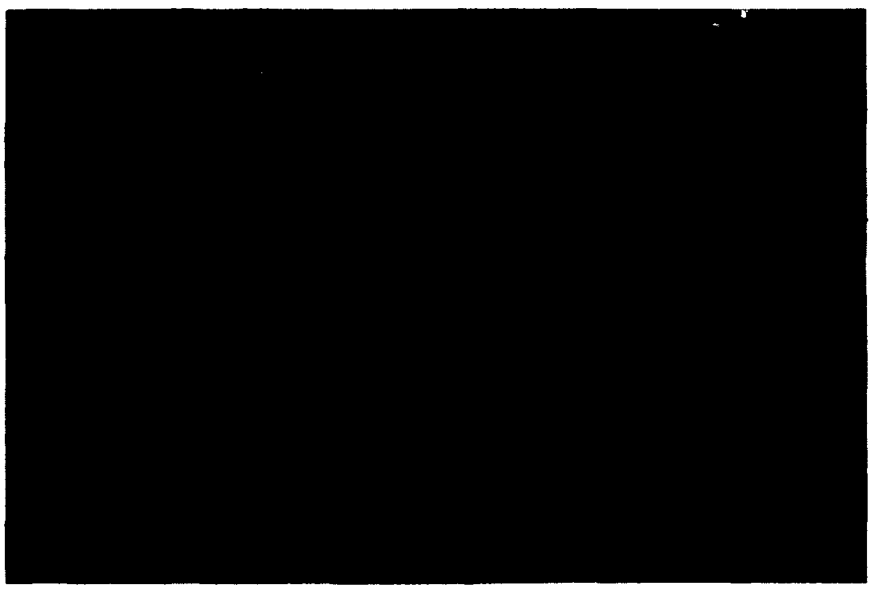
For the third batch, that includes several avionic improvements, a new set of symbologies was developed with the participation of Italian and Brazilian Air Forces test pilots with the new simulator configuration. The development symbologies where projected on to the dome, while the pilot was able to compare them with the standard ones using the real HUD installed in the simulator cockpit, dimming it as necessary.

9. The Training Potential

The problem of familiarizing the operational pilots with the new single seater fighter that was near to be delivered to the squadrons was considered by the Air Staffs of the two nations with some concern, since there was not yet a two seater version available and the possible purchase of training simulators continued being shifted in time schedule for the usual defence budgets shrinking.

On the other hand, at that time the AM-X Alenia flight simulator had reached the complete configuration described above and was well known to the staffs because of the several simulation sessions performed by their OTC's; so it seemed rather natural to guess some training was also possible with this simulator.

A minimal set of specific improvements was then required to make the simulator suitable for this application. The cockpit was completed also with those items of no use in the engineering simulator (like comm/ident facilities, ECS panels, etc.).



To overcome the lack of the motion system, considered important in a training simulator, it was installed a medium cost g-seat/g-suite system of the electromechanical/electropneumatic type, that proved rather effective, even if providing only "rough" feelings of the main motion cues.

Some special software was also developed; it was mainly necessary for the simulation of the utility systems and engine failures and malfunctions that again had been of no interest for the development activities, and for some pre- flight procedures.

Since operational mission training was also envisaged and familiarization with A/A modes was required, being the AIM-9L Missile included in the basic aircraft configuration as its self-defence weapon, a 5 DOF real time simulation model of the missile was developed and validated versus a very accurate non real time, 1 m/sec. increments model with good results.

Italian and Brazilian operational pilots began then to be trained on our simulator under monitor of their own instructor pilots and the technical assistance of Alenia simulation engineers.

Of course many improvements could still be done to increase the training capacity of the simulator, but the present configuration is considered by the users sufficient to perform:

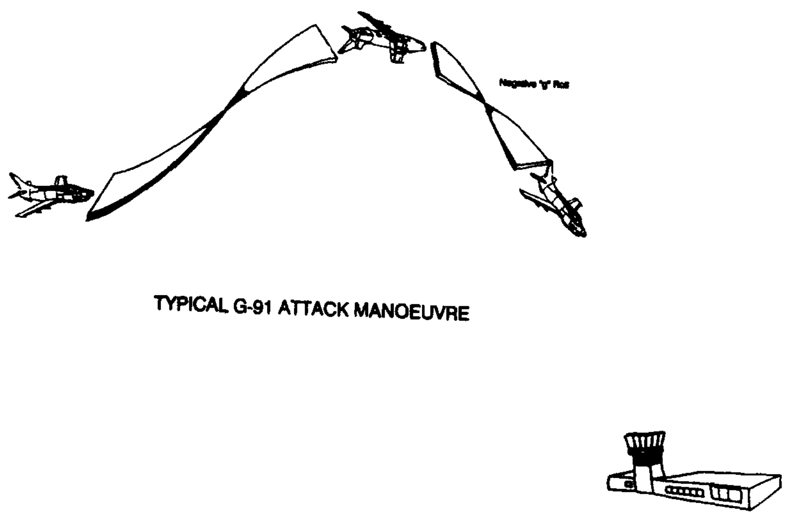
- normal and emergency procedures
- basic flight manoeuvres
- low level navigation and attack manoeuvres
- formation flight
- familiarization with A/A system characteristics.

The way in which practically this training activity takes place is rather unusual but has some interesting aspects.

The possibility of interaction between operational pilots and development engineers allows on one side the pilots to obtain clarifications about a lot of technical aspects more effectively than through the traditional training channels and on the other side engineers can have a useful feeling on what shall be the real use of the aircraft.

A good example of this interaction between training and development activities was a study about inertial coupling performed by flight mechanics department after some cases of uncontrollability following a particular manoeuvre occurred during training.

Some pilots, transitioning to the AM-X from the G-91, were performing "pop up" attacks in the same way they were used to with their former planes. The manoeuvre was started at high speed, low altitude, there was a pull up to a high nose up attitude, followed by a half roll and high "g" pull to a steep dive (the target was easily identified during this phase); the final manoeuvre consisted in a rapid roll at slightly negative "g" to point straight to the target (Fig. 9).



TYPICAL G-91 ATTACK MANOEUVRE

FIG. 9

RAPID ROLLING WITH NEGATIVE "G" ENTRY

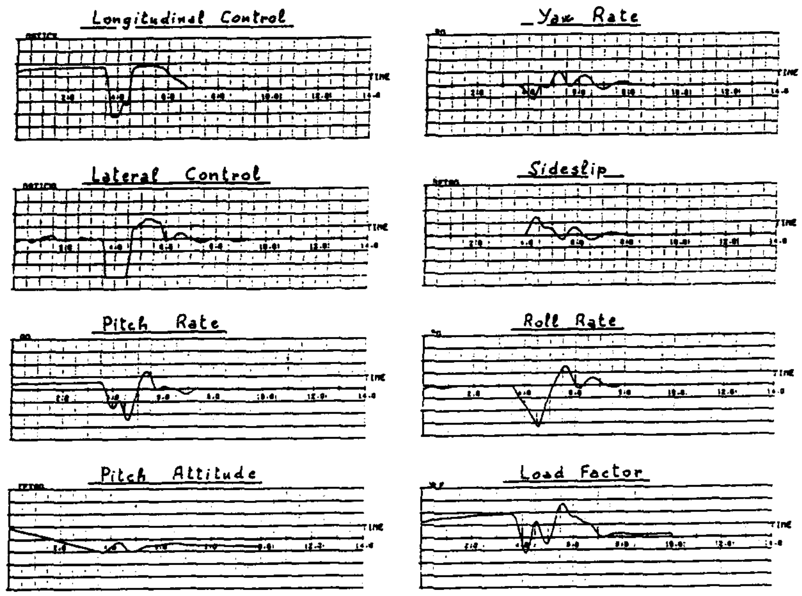


FIG. 10

Using the same control inputs they were used to apply in the G-91 resulted often in uncontrolled and unexpected development of yaw and roll rates.

The event was recorded and analyzed by flight mechanics engineers that easily clarified the situation. First of all,

RAPID ROLLING WITH NEUTRAL "G" ENTRY

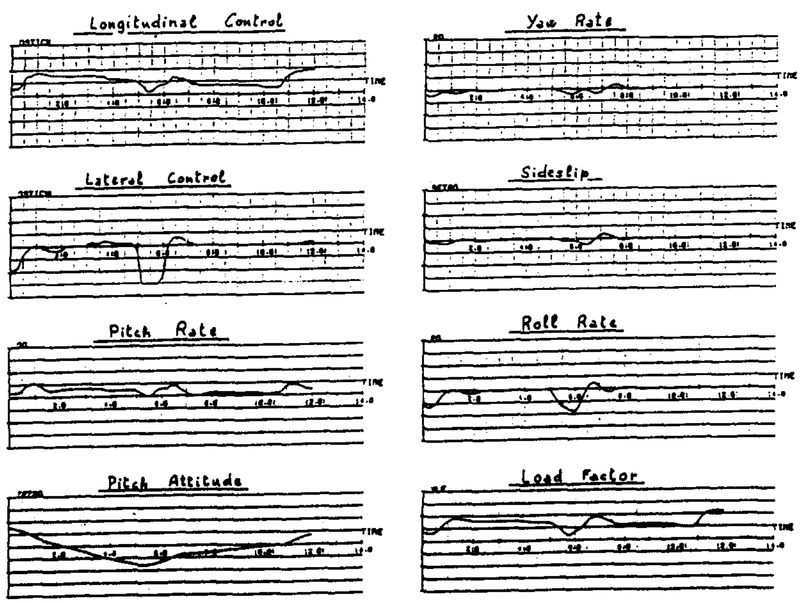


FIG. 11

the lack of an efficient negative "g" cueing on the simulator prevented pilots from feeling that the forward command during the inverted flight caused a much higher level of negative "g" than on the G-91. From this point, the high roll rate, coupled with the high pitch rate caused the development of a yaw rate that in turn generated a proverse sideslip; this and the increased spoilers effectiveness at negative angle of attack were responsible for the large amount of sideslip and extremely high roll rate.

All this was explained to the pilots and a recommendation was issued in the flight manual about the use of the pitch down command during rapid rolling. The required performance can be obtained with less extreme manoeuvres.

Figures 10 and 11 show the records of the main involved parameters before and after such recommendation.

The presence of a large population of air forces pilots with different experience and age was moreover the occasion for starting, sidewise, two research activities. One is a data collection about simulation sickness: a first emerging result seems to be that the more a pilot is a "natural pilot" or an experienced one the more he is subject to sickness, due probably to the feeling of cues different from his expectations. The second research, entitled "pilot errors analysis" is aimed to classify the recurring patterns that lead to frequent errors during the simulated missions and to correlate them to pilots' experience and workload of the moment. For this research the simulator sorties are monitored by a psychologist and pilot's actions and voice are recorded for further analysis. Main goal of the analysis is to identify to what extent the design of the pilot interface can be responsible of errors and how to define criteria to minimize this possibility.

10. Future Developments Activities

Since different new updated versions of the aircraft are currently under evaluation in order to expand its operational role, the simulator will continue being used to support development.

In this context, for example, some preliminary evaluations have been performed to assess the requirements on cockpit displays for allowing low level navigation at night.

The Compuscene three channels have been set to a reduced luminosity level to simulate dusk condition, while the fourth channel generated a simulation of infrared image as generated by an aircraft mounted FLIR system. This image is then projected on the dome in front of the cockpit with the same angular coverage as a real FLIR-compatible HUD.

With this configuration it has been possible to "fly" navigation sorties both in dusk and night conditions, evaluating FOV requirements for low altitude navigation in mountainous terrain. These tests are still under way, and they will soon include target tracking at night with a slewable IR sensor.

Development of a new nav/attack system configuration shall also require evaluation of new cockpit layout incorporating state-of-the-art displays and controls. To this extent, it could be possible that a new concept of simulator cockpit is required, to enable performing comprehensive evaluations of multi-functions displays and controls.

A solution currently being proposed is a sort of "active cockpit" using a CRT display to simulate the instrument panel. Using suitable graphic computers to drive simulations of displays and a touch-screen for pilot input, the facility should ease evaluations of different cockpit layouts and relevant presentation of information.

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2. "Flying Qualities Experience on the AM-X Aircraft", AGARD CP 508 from Quebec City (Canada) Symposium 1990.

List of Abbreviations

A/A	Air to Air
A/G	Air to Ground
A/P	Autopilot
CCIP	Continuously Computed Impact Point
CLS	Control Loading System
CGI	Computer Generated Imagery
ECS	Environmental Control System
FCS	Flight Control System
FD	Flight Director
FLIR	Forward Looking Infra Red
FOC	Full Operational Clearances
FMP	Flight Mechanics Panel
FOV	Field Of View
HOTAS	Hands On Throttle And Stick
IR	Infra Red
NDE	Navigation Data Entry
OTC	Official Test Center
PIO	Pilot Induced Oscillations
WCP	Weapon Control Panel

Full Mission Simulation: A View into the Future

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SUMMARY

The use of Engineering Simulation as a design support tool is becoming more prevalent in assisting design engineers in prototyping new concepts in advanced integrated helicopters. The primary goal in using Full Mission Simulation as a risk reduction tool is that it can provide significant insight into critical design areas. In this capacity, it allows the research engineer the means to review critical design issues and assess areas of high risk associated with air vehicle design.

The use of the Engineering Development Full Mission Flight Simulator will allow the design engineers the opportunity to view the future performance of the design air vehicle. This includes areas of both aerodynamic and operationally suitability. The use of representative flight simulators will allow major design issues to be resolved with a significant reduction in the cost normally associated with developmental flight testing. The performance of the air vehicle flight characteristics, flight control laws, and cockpit design can be evaluated in the safe and secure environment of the simulator before actual flight test. In this regard, the capabilities of Engineering Development Full Mission Flight Simulators have shown themselves to be an outstanding tool in evaluating advanced design aircraft during the initial design phase.

Today's use of statistical and multivarient analysis techniques provides the designers with a real time quantitative capability to collect and analyze data, thus reducing the risk associated with new product development. This paper identifies the methodologies used that provide the designers and pilots with the unique opportunity to evaluate different aircraft configurations in the Full Mission Flight Simulator before the design is concluded.

1. INTRODUCTION

The assessment of risk in advanced helicopter design is a very complex problem and not easily answered. Former Treasury Secretary George M. Humphrey is quoted as saying, "There are no hard decisions, just insufficient facts. When you have the facts, the decisions come easy." The use of Engineering Development flight simulators as a risk assessment tool in advanced helicopter and cockpit design is a practice that is becoming a norm during the design and analysis process. As helicopter systems become more complex and expensive to test, the helicopter industry is becoming more reliant on the use of simulations. Igor Sikorsky first used a flight simulator in the 1930's to develop attitude control of the main rotor system of his new flying machine, the V-300. With this simulator, he was able to perform aircraft controllability studies, arrangements of mechanical control interfaces, and control gearing requirements before the actual manufacturing process. Through simulation, he tried several iterations of flight controls including tail mounted rotors for pitch and roll control. His simulator did a great deal to teach him the piloting requirements necessary to control the new rotorcraft and other controllability issues of his first helicopter. Simulation will not replace early operational testing, however it will complement it by allowing an early look at the proficiencies of the aircraft system capabilities far in the lead of the design.

The modern day helicopter is becoming more advanced and the integration of mission equipment package is becoming more complex. The use of Full Mission Flight Simulation as an engineering development tool is also becoming more prevalent as a risk reduction tool. It affords an opportunity to evaluate the total system in an operational environment. This will provide decision makers the essential information that is necessary to assess the progress of the new systems towards fulfilling the operational needs of its users. The fundamental reason for this is the degree of complexity of these new aircraft and the tremendous cost incurred by aircraft manufacturers during the development of advanced airframe and avionics systems.

2. RISK

Risk is defined in many different forms, the specific application for the definition of risk depends on which discipline we are discussing. In its simplest form, risk is:

Risk = Probability x Severity x Weight

This formula states that for every event or action there is some unit of risk associated with that event or action. In a broad sense "the quantitative assessment of risk is defined as: a formulation

consisting of an engineering or scientific exercise...that is used...to identify potentially hazardous events associated with a given project and to estimate the risk in terms of the likelihood of occurrence and the severity of the consequences." When flight testing new aircraft, system design risks can be quite high with the resulting consequences very dramatic if something goes wrong. The primary goal of the Engineering Development Full Mission Simulation is to provide the data necessary to assess the risk during a preliminary design phase. This will allow the designer, in concert with engineering test pilots, to make decisions on whether the risks are such that the project should be pursued without additional risk control, or redesign project components when necessary to minimize problems. These are the decisions that must be weighed before pursuing the design of any system. These conditions are with respect to cost (research and development), capital expenditure requirements, and schedules vs. performance evaluations. An interesting article in Aviation Week pointed out: "Simulators are...used primarily for research...and as such are permitting managers to assess candidate technologies in a low risk environment before the start of flight testing."

3. BACKGROUND

A brief discussion of older helicopter systems will provide an insight into past structural and aerodynamic design requirements. Simply speaking, in the past, the airframe of a helicopter was an external shell of some material formed around a mass of dynamically moving parts. The specific shape of the airframe is driven by customer requirements for aircraft use. There are three basic categories of military helicopters. The most common types seen in the inventories today are utility, heavy lift, and attack.

The utility helicopter is generally a small, highly maneuverable aircraft with a dual position cockpit, single or dual engines, and a cargo compartment used to transport troops and/or supplies. These types of aircraft are used for light transport tasks or are used as an observation platform. The gross weight of these machines is usually around 18,000 pounds.

The heavy lift helicopter is a large aircraft with a dual position cockpit, two or more engines, large cargo compartment to carry pallets of equipment, other aircraft, vehicles, and troops. The gross weight of this type of machine can be upward of 75,000 pounds.

An attack helicopter is also a smaller aircraft and has a narrow fuselage similar to a modern fixed wing fighter aircraft. They generally have a tandem cockpit, dual engines, and externally mounted sensors and weapons systems. The gross weight of this type of aircraft is usually around 13,000 pounds.

Helicopters of the future will be more advanced than any other helicopter system ever designed. With the evolution of the modern mission equipment packages, the integration of avionics into future aircraft will be the most complicated task ever attempted. The future attack helicopter cockpit designs will accommodate an all-glass cockpit consisting of multifunction displays, touchscreens, and reprogrammable displays. These levels of automation will provide pilots greater versatility and capabilities for the completion of their mission. This implies that these helicopters will contain sophisticated avionics and electronics that are intended to decrease pilot workload by automatically assisting him in the performance of the mission.

The engineering development simulators are used during the development stage of the design to evaluate cockpit design (controls and displays), crew system interfaces, electronic flight controls, air vehicle handling qualities, sensor system location, mission equipment packages, helmet mounted displays, and pilot workload during specifically designed mission scenarios.

3.1 Air Vehicle Modeling

In the past, the design of helicopters required the efforts of numerous engineering disciplines to calculate the forces and moments that effect the flying quality contributions of every component of the helicopter. The exhaustive amount of data created during the design phase of the aircraft was referenced by each discipline in a specific succession. This requirement is due to the interaction of the aerodynamic forces and moments of one portion of the system on another. An example would be the handling qualities of the aircraft. They are effected by the downwash of the rotor system on the fuselage, the tail rotor and the empennage. There is also an effect of fuselage wake on the empennage's aerodynamic contributions that are dependent on the forward airspeed of the aircraft. There is a requirement for the aerodynamic system analyst to sum the component forces and moments that act on an aircraft's center of gravity to obtain body axes' accelerations. These accelerations are integrated into the velocities and attitudes that condition the environment for the calculations of the flight dynamics of the aircraft. Since the basic Laws of Physics remain the same, the creation of modular computer program models of specific components of the aircraft is inevitable. These models must be executed in the proper order as required by aerodynamic principles for an accurate simulation of a helicopter system. An example of a typical GENHEL Flight Dynamic simulation is seen in Figure 1.

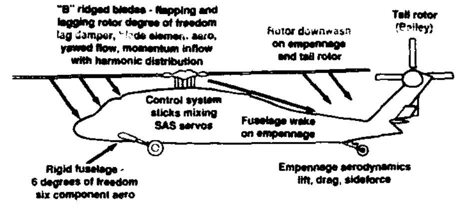

Figure 1. GENHEL Flight Dynamic Simulation

The significance of the mathematical modeling of the aircraft is of paramount importance if the proposed use of the Engineering Development Simulation is to have any validity. At Sikorsky Aircraft, a library based modular control and analysis modeling system called Master GENHEL is used. This library based system consists of the mathematical models representing all major components of the aircraft. These modules include the airframe in six-degrees-of-freedom. The flight dynamic models that are used to configure a basic aircraft are the rotor (with two basic types, complex blade element model, or a simplified rotor disc), engines, fuselage, horizontal tail, vertical tail, tail rotor, and a gear model. There is typically a mathematical model of the flight control system that simulates the primary Mechanical Flight Control System and an Automatic Flight Control System. An example of a GENHEL application is seen in Figure 2.

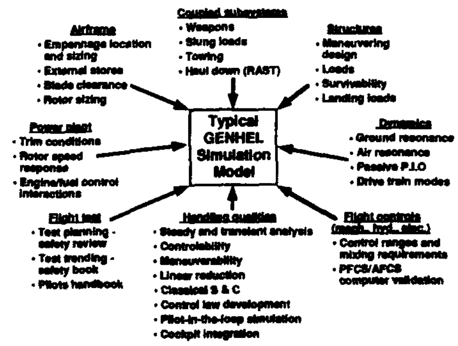

Figure 2. Typical GENHEL Applications

These flight control systems can be either analytical controller models of pilots, or a complex flight control system that models the actual proposed flight control system. The GENHEL simulation sums the component forces and moments that act on the aircraft's center of gravity to obtain the body axes' accelerations. Through numerical integration, velocities and displacements are used to condition the environment for the calculations of the flight dynamics for the next pass through the simulation model. The use of a library based system allows the design engineer to create a generalized modular, analytical representation of the design aircraft. The user creates a computer file of the aircraft functional model and then places these models into a specific order to insure that the proper inputs are considered for accurate module execution. The air vehicle model can be evaluated in the time domain and will allow the simulation of any steady or maneuvering flight condition expected to be experienced by the flight crew. The model has the capability of being flown through the use on analytical controllers. This provides the engineer the opportunity to perform parameter evaluation of aircraft performance with a model that does not have human variability. The simulation model is now capable of being flown with a pilot-in-the-loop for control system development and additional human factors crew systems evaluations. A typical GENHEL simulation is shown in the following example:

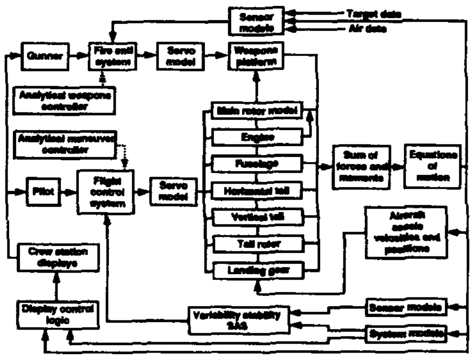

Figure 3. Typical GENHEL Simulation

The Master GENHEL's library based concept has been expanded to another modular library-based simulation called GENMEP, for General Mission Equipment Package. The GENMEP system allows a designer to add different mission equipment package systems into the simulation. These systems include all the basic systems expected on present day rotorcraft but are not limited to systems in the present inventory. There are Target Acquisition Systems, Pilot Night Vision Systems, Navigation Systems, including GPS, INS and Doppler Systems, Communications Systems including AM/FM/SSB and secured communication simulation, Aircraft Survivability systems including radar/laser warning systems, jammers, and weapon system simulations of 2.75 HYDRA 70 FFAR, HELLFIRE, Stinger and multiple gun models.

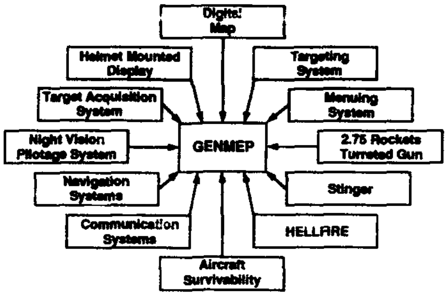

Figure 4. GENMEP

These weapon system models have been created at varying levels of complexity, based on the customer's requirements for a specific level of combat mission simulation. The algorithms for the weapons or tactics systems are fully coupled to the airframe's six-degrees-of-freedom. Helicopter motion is imposed on the weapons, and conversely, weapon forces and moments are applied back into the airframe. Weapons effects are simulated in the visual system to display tracer fire, rocket flyout, smoke, and projectile impact. Weapon scoring is included in the system software for analysis by engineers later. This weapon scoring is calculated on weapons impact positions, target vulnerability, weapons explosive loading, type of target, and the probability of hit (P_h) and probability of kill (P_k) data tables provided by the customer technical system experts. These provided tables allow for customer verification of weapons effectiveness.

There are many benefits to the use of a library-based system, however once this approach is selected, there is a requirement for total commitment to the program if the benefits are to be realized. These benefits are somewhat obvious. The modularity of a library-based system allows modules to be built, debugged, and tested off-line from the main system until the users verifies their operation. There is also the flexibility in that the generic modules developed for one program can be shared with another program that has similar requirements, thus reducing program cost and increasing program turnaround time. This flexibility also allows the user to select a complexity level that is appropriate for the level of sophistication required for the rotorcraft model that is under evaluation. A modular system will also allow a user to add modules easily without having to change the existing set of equations.

3.2 Controls and Displays

The cockpit of the engineering simulator is used to evaluate flight control switchology and display formatting before the actual design and coding for the aircraft. The Engineering Development Simulation is used to support the concept of Integrated Product Development because it allows the designer, test pilots, and the customer to converge in one area to evaluate future crew station designs. In the cockpit of older aircraft, there were individual switches for every function imaginable. Pilots were required to memorize where switches were and their functionality. This approach leads to the use of valuable cockpit real estate for switches that may be used once during the flight. Advanced crew station design provides the crew with reprogrammable displays that illuminate for specific functions only, thus informing the crew to provide only precise inputs to what is displayed to them. This design eliminates the requirement for multiple switches within the crew station that are only displayed when called on or needed. Cockpit designs are developed with engineering test pilots in the design loop, in concert with human factors engineers setting the requirements for placement of the displays and switches in the cockpit. Mockup cockpits are fabricated and tested anthropomorphically and ergonomically. Once the grouping of the switches are finalized and are satisfactory to both pilots and human factors personnel, mathematical stick shaping of analog and force transducer beeper switches are completed to optimize slew rates of the different sensors and cursors on the aircraft displays. Flight control switchology and placement of the controls can be flown during a simulated mission with modifications made as needed.

Cockpit display, formats of these displays, and cockpit designs are formulated early on during the development of a new aircraft. Different display formats are tested and changes made as necessary before the final design is established.

Large multifunction displays located in the crew station instrument panel include digital maps, that provide navigation information, threat and friendly information and location, hazards, flight plans, and other types of information that the present day pilot places on his paper map with a grease pencil. The most significant capability provided to the pilot is the ability to declutter the displays when an item is not needed. This can not be accomplished using a conventional paper map. Multifunction displays integrate display sensor imagery, tactical information and subsystem aircraft management information. Displays within the crew station can also inform the pilot what task he is executing, systems status, and options available while the other displays present system mode, weapons status, consumables, caws, incoming messages, and current radio configuration. It is through these displays, which replace numerous dial, gauges and switches of the past that the pilot uses to control his aircraft systems.

3.3 Electronic Flight Controls

During the preliminary design phase of flight controls, the controls' engineer designs the basic architecture for the flight control laws. These flight control laws are modeled along with the dynamic components (rotor blades, tail rotor, main rotor head) into the simulator. Once this

is accomplished, an engineering test pilot evaluates the design of the flight control system, both PFCS and AFCS modes. After the initial flight evaluation, stick shaping, gain and other control system issues are modified in real time, and then the flight control system maneuvers are reflown. This procedure will be repeated until the control system is optimized. Once the flight control laws are optimized in the simulator they can then be implemented in an actual flight control computer and evaluated in a test bed aircraft. By using the Engineering Development simulation as the primary, initial test vehicle, most of the initial risk of testing new electronic flight control laws is minimized.

This procedure has been used at Sikorsky Aircraft during digital control work performed on the SHADOW aircraft. By using this process very minor changes were made once the optimized versions of the flight control software were implemented on the aircraft. The pilot has the option of selecting multiple flight control modes from the automatic flight control system. The controller allows the pilot to control the aircraft in pitch, roll, and yaw when the primary automatic flight control system is selected. The full displacement collective is installed to provide the pilot response as to the amount of power he is placing into the rotor system.

Flight control systems have been flown in the engineering simulator at Sikorsky Aircraft for many hours and have then been transferred to a surrogate aircraft for final optimization in the future. The risk of developing and flying a new flight control system will be greatly reduced using this methodology.

3.4 Sensor System Design

The sensor system design and capabilities are a critical part of the crew's ability to satisfy critical mission performance requirements. The sensor system images presented to the flight crew should support their ability to fly the aircraft and increase their situational awareness and ability to satisfy mission requirements. With respect to the flight control issue, the simulation sensor system should have the minimum capability to present a visual image of such quality to the pilot that it will allow him to aggressively maneuver the aircraft with precision and confidence. Crew station situational awareness, with respect to a sensor system, could be defined as the crew's ability to fly the aircraft at low levels with confidence. They should be able to detect threat weapon systems, both air and ground, at acceptable ranges and be capable of selecting the appropriate terrain features within the database for low level flight and navigation purposes. The simulated sensor system should be capable of replicating the performance of both thermal imaging systems and image intensifying systems.

The Image Generation system used at Sikorsky Aircraft is a General Electric CompuScene IV with video post processing systems. These post-processing systems provide a capability to take the video image of the out-the-window database generated by the C-IV and make the proper visual adjustments to replicate second generation sensor systems. It should also be capable of simulating the proper sensor system placement on the air vehicle or within the crew station, the gimbal rates of the sensor, its accelerations, and gimbal limits.

The Engineering Development Simulation facility's capability to replicate the performance of the newer generation sensor systems is essential to proper performance evaluations. The system should provide a visual sensor system simulation that closely replicates the actual sensor system, either FLIR, LLLTV or DAYTV. The effectiveness of the sensor system for different crews can now be evaluated for issues of effectiveness concerning pilot workload, with an ability to modify Field of View, Field of Regard, resolution, sensitivity, auto/manual gain and level adjustments and the primary issue of flight symbology placement and content.

3.5 Tactical Environment

The Tactical Environment that the Full Mission Simulation is evaluated in is of premier importance to the evaluation of crew system interaction and mission effectiveness. It is imperative that this environment is as realistic as possible, that the threat's tactics, capabilities, acquisition and tracking probabilities and lethality are as realistic as possible. The design of the GENWORLD modular Tactical Environment at Sikorsky Aircraft takes these issues into consideration at the conception of design. The GENWORLD system allows for a quasi-intelligent threat capability that is controlled in a high speed computer system. This system is capable of controlling customer designed and directed mission scenarios replicate of many-on-one tactical missions. GENWORLD has the capability of controlling a large number of multiple active threats in the tactical database. It also has the capability of networking multiple medium fidelity man-in-the-loop simulators with the moving base ownship. The whole objective of the use of the GENWORLD system is to provide controlled, realistic tactical mission stimulus to the evaluation crew while they perform their mission. The final goal is to force the evaluation crew to perform mission oriented decisions so their operational workload can be evaluated in post-flight analysis.

The threat sensor system capability is a very important part of Full Mission Simulation in that the sensors' capabilities provide information such as position, velocity, identification, and weapons employment status. These simulated sensors must replicate the actual capabilities of the environment that the crews are expected to perform in. The sensor within the GENWORLD environment is broken down into three functional areas, (1) the

detection model; (2) the observable model; and (3) the sensor fusion model (simplified).

The detection model has an algorithm that has the ability to detect all threat radars with a specified range, based on signal strength previously defined within the system tables, including Electronic Surveillance Measurement, Radar/Laser Warning, Infra-Red and Electro Optical Imaging.

The observables model that is used in the GENWORLD environment includes RF (radio frequency), IR, and man-in-the-loop visual acquisition. For the active RF sensors, customer provided lookup tables for Radio Cross Section (RCS) of their specific air vehicle are used. These tables can include RCS values for azimuth and elevation cuts, however, these tables are not required to be uniform in nature, and each table has an associated frequency band respective of the aircraft.

The IR sensors in the GENWORLD environment also use a user provided lookup table for determining an aircraft IR signature as defined by elevation and azimuth angles specified for each specific IR sensor's characteristics.

The optical sensors and unaided visual detection capabilities are modeled based on air vehicle size determined from the out-the-window visual object data tables, and are used in the optical detection algorithms.

GENWORLD provides the capability for air-to-air, air-to-ground and surface-to-air missiles' engagements using active seekers, a generalized guidance control computer, a five-degree-of-freedom motion simulation for the missiles, a data table driven propulsion model, and a lethality model. Missiles are selected with the appropriate parameters' requirements being satisfied.

The seeker models provide the measurement of line-of-site angles and angular rates between the missile and the target, including the missile guidance functions. The seekers work in the RF, IR and EO regions, including:

- semi-active radar
- anti-radar
- active radar
- image radar
- home-on-jam
- electro-optical
- IR
- command
- laser

Seeker parameters used include:

- tracking loop time constant
- scan parameters
- detection model parameters
- gimbal limits
- instantaneous field of view

The missile guidance models of the GENWORLD system take seeker line-of-sight rates and computer flight simulation inputs into consideration as the system attempts to maintain the desired navigation laws including:

- proportional
- lead pursuit
- pure pursuit
- bias pursuit

The guidance parameters of the GENWORLD system include:

- guidance activation time
- time constant
- lead or offset angle
- output limits

The propulsion systems of the GENWORLD missiles are modeled from either velocity curves or thrust time history with current drag used to determine the missile velocity. The thrust/drag modeling parameters include:

- multiple stage rocket motor with mass, time, and specific impulse for each stage
- induced drag curve
- burnout weight
- skin drag

At the missile intercept of the target, GENWORLD will evaluate the damage to the target. This evaluation considers the closest point of approach method, with additional criteria for a valid intercept. This information is fed back into the simulation data collection system for post-flight mission effectiveness analysis. The fidelity and capabilities of the threat acquisition systems can be controlled for lethality and acquisition by customer data tables.

The gun system is a simplified model that uses an idealized projectile with aerodynamic drag for flyout. There is an application of a randomization of projectile position at intercept time for the P_k and P_k evaluation. The gun system in the GENWORLD environment can fire in either a continuous mode or in burst. The gun's fire control computer is modeled by varying the predicted intercept point as a function of the data available to the fire control computer. The target position, velocity vector, acceleration, range and range rate are data sets that effect the gun's accuracy and are under customer control. The gun parameters that are used by GENWORLD include:

- ballistic coefficient(s)
- maximum time of flight
- rate of fire
- stores load out
- slew angle limits
- slew rate limits
- muzzle velocity

All data parameters used by the GENWORLD system are available to the simulation

facility data collection system. This information can be used in the post flight analysis of variance of pilots capabilities vs. specifically established threat systems.

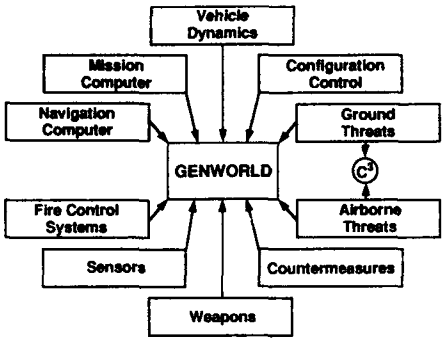

Figure 5. GENWORLD

3.6 *Data Collection Analyses Techniques*

Through the use of multivariant analysis, management has the opportunity to use quantitative methods to reduce the risk associated with new product development. It is with full scale flight simulation that managers have the opportunity to collect the appropriate quantitative data necessary to perform trade studies and make tradeoffs in aircraft design that were never before possible. Management can now have the aircraft and cockpit designed and tested in a replicate flight environment. Pilots can fly a specifically designed mission scenario in the simulated tactical environment to provide evaluations of system performance. They now are provided a chance to flight test the systems in a Full Mission Simulator where the aircraft is performing a realistic mission. The obvious advantages of this are that the whole system can be checked before the "real" aircraft is built.

The use of multivariant analysis requires that two simple rules be followed:

(1) The user is aware of the data requirements of each method.

(2) The users outline the questions to be answered before starting the analysis.

It is essential in a large scale research and development effort that key issues be defined well in advance. An accurate definition of the test task gotten to be established to allow for proper planning and accomplishment of the goals of the research effort. Issues of what data will be taken, at what rate, what qualitative assessment questions will be asked, and what specific issues are being addressed must be established. The amount of technical data that is possible to collect during flight simulation evaluations is unlimited. Data can be collected about the evaluation ownship, and the threat vehicles. A sample of a typical Air Vehicle data table follows:

Aircraft Data	A/C Control Data	Rotor States	Engine Para
body & ground axis	stick position	main rotor	Turbine speed
position	stick rates	flap angles	engine gov.
velocity	stick forces	flap rates	speed fuel flow
accelerations	servo positions	lag angles	rate engine
angles	servo rates	lag rates	acceleration
rates	rotor head	rotor speed	
position errors	position	rotor acceleration	
sideslip		rotor loads	
angle-of-attack		rotor stall	
load factor		fan states	
		fan load	
		fan power	
		required	

An example of a typical Mission Equipment Package data table is shown:

Continuous Data	Evaluation Ship	Threat Data
position N, E, alt	designator	type
flight path error	waypoint	velocity
ground speed	reported location	position N, E, alt
altitude	MEP target classification	LOS to ownship
	reported threat identification	lethality
	reported location	
	range to target	

The aircraft can be evaluated performing numerous flight operations in a controlled environment. It is this type of evaluation of air vehicle performance that can reduce the cost of aircraft design by unlimited amounts of funds. It can provide an alternative means of budget control and risk reduction for program managers that was unavailable in the past.

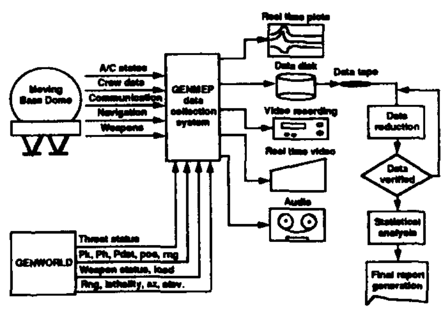

Figure 6. GENMEP Data Collection System

The perception of risk and the criteria for evaluating areas of high risk differ for every manager. A major objective in the field of risk assessment is the development of a uniform definition of risk. As stated previously, in a program such as aircraft design, there are many stages. Each manager perceives risk in his area in a different way based on experience, frequency of occurrence during past development programs, etc. An important fact that each manager should remember throughout the development of the program to make a sound decision is the objectivity of the level of risk involved. Someone said that "...the perception of risk is itself an extremely complex process. Objective facts and evidence

come into it but it is the meaning of the evidence which is important." The engineering flight simulation supports the decision making procedure by allowing the manager and his staff the opportunity to evaluate the actions of a flight crew as they perform specified actions in response to controlled criteria. This is critical to multivarient analysis because, for the first time, a helicopter design team is capable of being in proximity to the flight crew, and can observe them as they perform a mission. The test criterion is controlled, and there is time to evaluate a multitude of pilots performing the same mission. It is with data such as this, using fleet pilots rather than engineering test pilots, that the manager can assure that the system being designed will properly perform its mission functions in the field, and thus the lessen the risk of redesign.

3.7 Tactical Simulation Center Operations

The Tactical Simulation Center was designed to support the command and control functions of the multi-role capabilities of the simulation facilities. It can provide a centralized monitoring position for simulated air-to-air, air-to-ground, and cooperative weapons deliveries. It is the controlling nerve center for interactively accessing the medium fidelity players stations, the Fixed Base Simulator, the Motion Base Simulator, the Test Director's Area, and the Tactical Operations Center. It is the one center position where the entire simulation process can be monitored and controlled by the Program Management staff. They are afforded an opportunity to overview the complete simulation experiment as the tactical simulation scenario unfolds. The Tactical Simulation Center has complete communications with all active players in the experiment plus the test director's area. It also allows the Program Management staff to monitor the relative positions of all players plus the evaluation ownship, with respect to the mission plan from a God's Eye view point on a tactical map. A complete series of visual monitors shows the Program Management staff replicate video of what the crew sees in the evaluation cockpit. All simulation data collection systems are controlled and monitored from this central area.

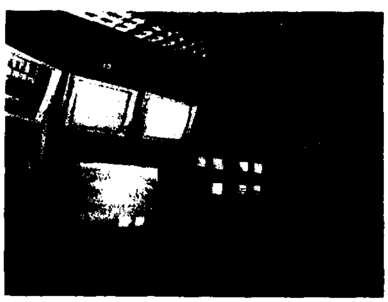

Figure 7. Tactical Simulation Center

The Tactical Simulation Center is designed to provide an environment that will allow the proper conduct of a full mission experiment.

3.8 Facility Operations

The facility operations consists of a 6 degree-of-freedom moving base platform with a 20-foot all composite dome structure rigidly attached to the platform. The visual projection system consists of three Talarian light valve projectors 180 degree horizontal field of view by 80 degree vertically around the pilot's design eyepoint. The 80 degree vertical FOV is projected 50 degrees downward and 30 degrees upward from the design eyepoint. The downward FOV supports provide critical ground perception cues necessary for the NOE pilot, while the upward FOV satisfies limited helicopter air-to-air. The simulation cockpit contains a seat shaker system that provides high frequency cueing to the pilots in the 3 to 40 hertz range at .5 g's in the vertical axis. The seat shaker vibration algorithms are designed to simulate high frequency cues to the pilot that cannot be satisfied by the motion system, such as translation lift, rotor speed changes and rotor stall, velocity cueing, load factor, droop stop pounding, and weapons effects, both for delivery and impact. The simulation aural cueing system is designed to support the Full Mission Environment. It provides the cueing sounds typically associated with the operational flight envelope, such as rotor, transmission and slip stream sounds, wheel rumble of a tarmack, landing gear deflection, and gear lock. The cueing system also simulates those sounds attributed to weapons deliveries, such as gun firing and rocket launching sounds, including system malfunctions. The moving base system is a 6 degree-of-freedom, 60 inch excursion system that accelerates at approximately 400 degree per second rotationally on average and 1.1 g translationally. The bandwidth of the system is fairly flat to 4.5 hertz, with a substantial roll-off above 5 hertz. The moving base drive algorithms utilize a system of adaptive washout to provide realistic motion cueing within the limits of the system. These algorithms allow the platform to be accelerated to a commanded position, and then will allow the total system to be returned to a near neutral position below the perception of the pilots. This allows the pilots to now input an additional control input, and will allow the system to respond appropriately. This type of algorithm allows the scaling, limiting, and high pass filtering of motion commands so that the realtime motion filtering is a function of the present simulator commanded conditions. The moving base flight simulation is designed to provide the simulated environment necessary for the final evaluation for Full Mission evaluations.

Figure 8. Motion Base Dome

3.9 Full Mission Environment

Full Mission Simulation is the core element necessary to satisfy the requirements for Operational Test and Evaluation of future aircraft and crew systems design. The full mission environment is designed so that a customer can establish the type of mission and the combat scenario, the threat laydown, and the activities of the threat vehicles. This is designed so that the evaluation crew will be analyzed against systems that they are intended to be analyzed against. All capabilities of the threats, their acquisition ranges, P_k, P_h, and lethality can all be controlled by customer provided data tables, either classified or unclassified. The interactive threats, both computer modeled and man-in-the-loop, can be validated against the standard doctrine of the threat environment that the customer wishes for his crews to be tested against. An opportunity to determine tactics and classified weapons system delivery that is not presently available on open air ranges is now available in validated Full Mission Simulation facilities. The cost savings allowed through the use of Engineering Development simulations, in terms of weapon systems, are substantial given the price of the modern day smart weapons used by the military services. An obvious advantage is the capability of mission evaluation against a specified threat weapon system for the assessment of mission effectiveness and operational suitability. An example of a typical battlefield environment that can be designed is depicted below:

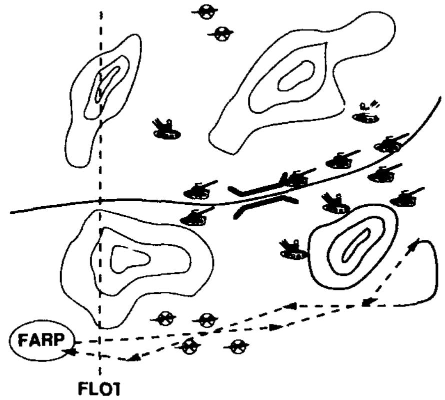

Figure 9. Battlefield

Systematically, the philosophy of the Full Mission Simulation is to provide as close to a real world threat environment as is possible in a simulation. The fidelity of the design of the Full Mission Simulation environment at Sikorsky Aircraft can provide as high a threat environment that has ever before been available to evaluation pilots.

3.10 Cost Control

The cost of the advanced development of a new aircraft is an expensive proposition for any organization. It is generally an activity that is directed towards a potential product that is designed and engineered for a targeted market area. This is the most important reason that Engineering Development Simulations are used in risk reduction.

The tremendous cost associated with aircraft design must be weighed by management as to the cost vs. the expected benefits. When management estimates the cost of flight testing, the budget year has a month-by-month accounting of labor and materials. "In establishing the budget for a future period, a beginning estimate can be made by using the total manpower cost, the material cost, and an overhead figure." It should be apparent that there is tremendous cost savings' potential by reducing the costs necessary for the R&D effort through the use of the simulation. It is the risk reduction capabilities that are provided with engineering development simulations that make the cost of a developmental simulation station cost effective.

4.0 CONCLUSION

The major consideration in the design of an engineering flight simulator is how you design for the future. How will aircraft of the future perform (turn rates, roll

rates, airspeed etc)? "Engineering simulators cost much more than their training brethren, but the leverage they exert in terms of development efficiency is such that risks and cost can often be dramatically reduced and hidden mission potentials revealed." One of the most important aspects of the engineering flight simulator that should not be forgotten is that the aircraft flight model (math model of dynamic systems, sensors and MEP) must simulate aircraft operations. If this is not true, or the math model is incorrect, the simulation will be useless as an evaluation model. The accuracy of the simulation is critical because "the objective is to give a clear picture of the relative risk and the probable odds of coming out ahead or behind in view of uncertain foreknowledge." It is concluded that the use of Engineering Development Simulation systems can significantly reduce the risk associated with advanced aircraft design. These systems can give management a view into the future performance of the aircraft, both aerodynamically, and physiologically. The most highly advanced aircraft is not worth its mettle if a crew is not capable of performing their mission. Through the use of the simulator, cockpits can be designed, and redesigned when necessary, at a significant reduction of the cost associated with flight worthy design principles. Flight performance characteristics can be studied in a totally safe and secure environment before actual flight testing. It is these capabilities that allow management to prove the value of an Engineering Development simulator in advanced aircraft Research & Development.

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FULL MISSION SIMULATION FOR RESEARCH AND DEVELOPMENT OF AIR COMBAT FLIGHT AND ATTACK MANAGEMENT SYSTEMS

92-15972

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SUMMARY

A description is presented of the analysis approach for an advanced development program using a realtime, pilot-in-the-loop air combat simulation. The program is developing and demonstrating advanced on-board flight and attack management algorithms to assist the pilot when outnumbered in air-to-air combat. A highly flexible simulation architecture allows hosting the flight test computer code in general purpose simulation computers. The simulator cockpit stations are modified to emulate the advanced pilot vehicle interface. A data collection and analysis approach is described which isolates and measures the effects of the various systems making up the advanced fighter concept.

LIST OF ACRONYMS

AASPEM	Air-to-Air System Performance Evaluation Model
ACES	Air Combat Engagement System
ACFMS	Air Combat Flight Management System
AMRAAM	Advanced Medium Range Air-to-Air Missile
APM	Aircraft Performance Monitor
AWACS	Airborne Warning and Control System
BPD	Battle Perspective Display
BVR	Beyond Visual Range
CAMAC	Computer Automated Measurement and Control
CDB	Central Data Base
CIC	Close-In Combat
CPU	Central Processing Unit
DAM	Defensive Assets Manager
ESA	Electronically Scanned Antenna
FDD	Flight Dynamics Directorate
FEBA	Forward Edge Battle Area
IAM	ICAAS Attack Management
ICAAS	Integrated Control and Avionics for Air Superiority
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IFFC	Integrated Flight/Fire Control
IIC	ICAAS Integration Computer
IPU	Internal Processing Unit
ISC	ICAAS Support Computer
IRST	InfraRed Search and Track
LAMARS	Large Amplitude Multimode Aerospace Research Simulator
MOE	Measure Of Effectiveness
MOP	Measure of Performance
MS-1	Mission Simulator 1
NM	Nautical Miles
PVI	Pilot Vehicle Interface
RMAX	Range, Maximum
RNE	Range, No Escape
SGI	Silicon Graphics Inc. computer
SWAT	Subjective Workload Assessment Technique
USAF	United States Air Force

I. INTRODUCTION

The United States Air Force (USAF) Flight Dynamics Directorate (FDD) recently began conducting full mission simulations to evaluate the tactical benefits of new aerospace technologies and integrated systems under development in Air Force laboratories. The simulation capability provides a realistic air-to-air threat environment combining both pilot-in-the-loop simulators and computer-controlled digital aircraft. A flexible computer architecture results in a powerful computational capability for aircraft, sensor, weapon, and pilot decision logic modeling. Two high-fidelity dome simulator crew stations are supplemented by four low-cost Manned Combat Stations to sustain a highly interactive threat environment.

During late 1991, evaluation of the Integrated Control and Avionics for Air Superiority (ICAAS) program will begin at the FDD simulation facility. ICAAS is an advanced development program formulating and demonstrating on-board attack and flight management systems designed to dramatically increase the exchange ratio in air-to-air conflicts. Aiding the ICAAS system's synergistic effect is an advanced pilot-vehicle interface consisting of an all-glass cockpit, low-profile head-up display, and helmet-mounted display. The ICAAS system includes an advanced sensor suite managed by a computer which generates multi-sensor track files and combines them with track files from other ICAAS-equipped aircraft obtained through a local area data link. The fused sensor data is displayed to the pilot on a situation display and also passed to the air combat flight management system. Here the computer evaluates the tactical situation and generates a ranked list of feasible air-to-air tactics from which the pilot may select one to execute. An optimal flight path is generated for the selected tactic and flight director cues are displayed to the pilot. The intent of ICAAS is to guide the aircraft to a first launch position with the highest degree of survivability possible.

A series of government and contractor ground-based simulations will measure the increase in air combat effectiveness of an aircraft equipped with the ICAAS system. Many different scenarios and missions will be used during the evaluations against a variety of threats. In addition, a flight test program will be conducted to demonstrate the maturity of the ICAAS technologies during which modified F-15s equipped with the ICAAS software will face a number of real and synthetic threats. This paper describes the FDD's ground-based air combat simulation of ICAAS.

II. ICAAS PROGRAM OVERVIEW

The ICAAS program objective is to enhance the air-to-air fighting ability of today's pilot by integrating technologies to give him increased situational awareness and to help him achieve a positional advantage over the enemy. The ICAAS objective is further defined as enabling an ICAAS equipped flight element to increase its combat effectiveness by 25%, as gauged by predefined measures of effectiveness. The flight test version of the ICAAS software will execute on two flight-worthy computers (each with three processing units) and interface to the pilot through a sophisticated pilot-vehicle interface (PVI) consisting of three multi-function head-down displays, a low-profile head-up display, and a helmet-mounted display. The middle multi-function display is 9.5 X 9.5 inches in size, color capable, and has a touch sensitive surface. The ICAAS software, being designed and developed in the Ada language under contract for the USAF by McDonnel Aircraft Company, will be tested first in ground-based simulation and finally in flight test.

The ICAAS system consists of four major components: ICAAS Attack Management, Air Combat Flight Management System, Integrated Flight/Fire Control, and Air Combat Engagement System. The ICAAS Attack Management (IAM) system controls all the aircraft sensors (radar, infrared search and track, and electronic warfare sensors), performs sensor multi-source integration, maintains track files, and executes fire control functions. In addition, the amount of available information is increased by the use of an intra-flight aircraft internetting system to share sensor information. The IAM is designed to significantly reduce pilot workload and increase situation awareness by integrating all the data generated by each individual sensor and presenting to the pilot a single, coherent picture of the tactical situation. The pilot maintains control of the sensor volumes, emission mode, and missile launch decisions. The IAM fire control function calculates missile launch opportunities and provides aim-dot steering for the pilot. The baseline weapons for the ICAAS program are the AIM-120 AMRAAM, AIM-9 Sidewinder, and 20mm gun.

The second major component of ICAAS, Air Combat Flight Management System (ACFMS), can be further broken down into five primary modules. The first is the Tactics Algorithm which has two principal functions: tactics selection and tactics monitoring. Based on the current tactical situation, as assessed from sensor and data-linked information, several tactics with associated figures-of-merit are generated by the algorithm and presented to the pilot for selection. Each tactic is designed to direct the aircraft to a first launch opportunity against the enemy aircraft. Once a tactic has been chosen by the pilot, the Tactics Algorithm monitors the progress and success of the selected tactic and continually updates the figure-of-merit. If the figure-of-merit falls below a pre-determined threshold, the algorithm begins a search for a better tactic.

The second primary module of ACFMS, the Attack Guidance algorithm, constructs a flight profile to achieve the selected tactic and monitors flight progress to insure the profile is being followed. This algorithm predicts launch points and missile impact zones which result from the tactics selected, the targets assigned, an assumed threat response, and the launch and guidance steering philosophy employed. Associated with each assigned target are projected kill and survivability metrics to assist the pilot in assessing the status of the engagement. Attack Guidance considers all threats in the area when calculating the attack profile, not just the highest priority target.

The third ACFMS module is the Defensive Assets Manager (DAM) which provides the pilot with a coordinated defensive response to an inbound air-launched threat missile. Defensive response options include early kinematic maneuvers, midcourse missile seeker defeating maneuvers, and endgame evasive maneuvers which may include active countermeasures and expendables. On-board sensors must detect the in-bound missile and the DAM scheduler determines which missile poses the highest threat to the ownship. A ranked ordered set of evasion options is generated and the top ranked option is recommended to the pilot. Flight director cues are presented to the pilot on the head-up display to assist in precisely timing the evasion maneuver.

The fourth ACFMS module is the Aircraft Performance Monitor (APM) which provides two basic functions. First, it generates energy maneuverability information for Tactics, Attack Guidance, and Defensive Assets Manager to assist in engagement predictions and to supply agility metric information to the pilot though the head-up or helmet-mounted displays. The second function of the APM is to anticipate life threatening hazards and provide a recovery procedure when the hazard is detected. Hazards include ground proximity and mid-air collisions.

The fifth ACFMS module is the Control Coupler. If selected by the pilot, the aircraft's flight control system will 'couple-up' to the ICAAS system and be flown automatically along the attack profile, evade missiles if necessary, perform gunnery steering solutions, and avoid ground or mid-air collisions.

The third major component of ICAAS is the Integrated Flight/Fire Control (IFFC) system which provides the pilot with a director gunsight for close-in combat with the 20mm gun. IFFC has both a coupled and uncoupled mode. IFFC has been previously developed and successfully demonstrated in a live-fire flight test program (Reference 1).

The last component of ICAAS is the Air Combat Engagement System (ACES) which will be used during the flight test portion of

the ICAAS program. ACES provides an on-board air combat environment in which to conduct the ICAAS scenarios. The system will generate synthetic targets and drive the ICAAS aircraft avionics and cockpit displays as though the targets really existed. The synthetic aircraft have maneuverability and weapons firing capability. ACES is disengaged during ground-based simulations as all the threat aircraft are provided by high-fidelity simulation on ground-based computers. The interested reader is directed to Reference 2 for a more detailed description of the ICAAS program.

The ICAAS contractor is responsible for designing and developing the ICAAS software as well as evaluating the mission effectiveness of ICAAS equipped aircraft in ground-based simulations. Furthermore, the ICAAS contractor will conduct a government sponsored flight test program to demonstrate in actual flight conditions the tactical impact of the ICAAS system. The USAF FDD simulation is being used to validate the contractor simulation results and to provide the opportunity to expand the simulation test matrix. For much of the government testing, the FDD simulation software and scenario conditions are identical to the contractor's to permit comparison of contractor and government simulation results. However, once the verification stage of the government simulation is complete, the flexibility of the government facility will allow many additional combinations of threat aircraft, weapons, and sensors to be used. In addition, threat aircraft will be flown from one of the dome simulators to equalize any advantage an ICAAS pilot flying from a dome may have.

III. DESCRIPTION OF FDD SIMULATION FACILITY

Simulation research is evolving toward a multiple aircraft, full-mission simulation capability due to two important requirements for future aircraft systems: the pressing need to integrate the aircraft's flight, fire, and avionic systems and the need to develop cooperative air combat tactics. To support these needs the FDD's simulation facility has recently greatly expanded its air combat simulation capability. The facility equipment can be divided into three broad categories: fixed and motion-based simulators, general purpose simulation computers, and special-purpose graphic generation computers. On the software side, a flexible air combat simulation has been developed to serve as the foundation for particular studies, such as ICAAS.

Fixed and Motion-Based Simulators

The facility has a large fixed-based dome simulator (the Mission Simulator 1 (MS-1)), a high acceleration motion-base simulator (the Large Amplitude Multimode Aerospace Research Simulator (LAMARS)), and four low cost Manned Combat Stations (MCSs). Both the LAMARS and MS-1 contain high-fidelity cockpit stations. The LAMARS is a beam-type, motion-base dome simulator, shown in Figure 1. Its past applications have concentrated on high-fidelity, handling qualities studies. For its use in air combat simulation, the electronics of the slewable, high-resolution target projector were updated and two laser target projectors were added, as well as a helmet mounted display. For the ICAAS experiments, the entire cockpit front panel is drawn by a graphic computer and presented to the pilot on a 29" high-resolution color monitor which has a touch sensitive screen. The head-up display symbology is projected on the dome surface at the correct pilot design eye position and field-of-view.

FIGURE 1. LAMARS Simulator

The MS-1, shown in Figure 2, is a state-of-the-art, 40 foot dome simulator designed specifically for air combat simulation. The MS-1 features four laser target projector pairs, a high-resolution target projector pair, two background projectors, and a slewable area-of-interest projector. It also can be equipped with a helmet mounted display.

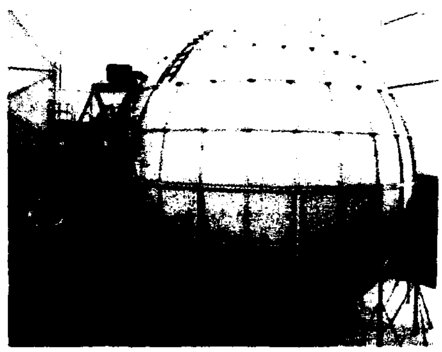

FIGURE 2. MS-1 Simulator

The high-resolution target image is generated by a Silicon Graphics 340 VGX computer while the background imagery for the MS-1 is produced by a Compuscene IVa image generator. The MS-1 cockpit is identical to the LAMARS cockpit for the

ICAAS program. The MS-1 and LAMARS simulators are typically used as a lead/wingman flight element, although it is possible to conduct 1v1 engagements between the domes.

It is desirable to include as many actual pilots in an air combat simulation as possible (as opposed to relying on computer controlled aircraft). However, the expense of modern large dome simulators precludes having very many of them. To get more pilots involved in the simulations, FDD followed the standard industry practice of developing Manned Combat Stations, as shown in Figure 3. To provide the pilot with familiar throttle and stick controllers, authentic F-15E throttles and stick grips are installed. The stick grip is mounted to a joystick controller in a sidestick arrangement. No rudder pedals are included in the MCSs.

FIGURE 3. Manned Combat Station

The cockpit displays and out-the-window visual for a MCS are generated by a Silicon Graphics 4D/85GT and presented to the pilot using a 19" color monitor. An advanced, all-glass cockpit with three simulated multi-function displays, a head-up display, and out-the-window visuals is displayed on each MCS monitor. Sensor data is presented to the pilot on a situation display to indicate range and azimuth to targets, as well as target heading. If deemed necessary, additional target information such as altitude, speed, and type of threat can easily be presented to the pilot. The situation display also indicates the position of friendly and neutral forces. These displays are intended to be used during the Beyond Visual Range (BVR) portion of an engagement. For Close-In Combat (CIC), an entirely different display was developed to enable the MCS pilots to effectively perform CIC with pilots flying in the dome simulators. This display uses a number of techniques to provide the pilot with 4-pi steradian line-of-sight knowledge of threat position and attitude. The pilot can switch between the BVR and CIC display formats depending on the given situation and informational needs.

A series of tests were run to compare the tactical effectiveness of a pilot flying from a Manned Combat Station versus a pilot flying from the MS-1 dome simulator. Information, above and beyond what is usually available to a pilot, was presented to the MCS pilot to bring his situation awareness up to the same level as the dome pilot. This is especially difficult to accomplish during the close-in combat phase of an air battle. However, with sufficient training on the special CIC displays, MCS pilots can learn to dogfight effectively with threat aircraft.

All of the simulators share a common analog and digital input/output architecture for interfacing the computers to the stick, throttles, and associated switches. This commonality eases maintenance and allows component swapping if problems arise. The fiber optic architecture is based on an IEEE standard called Computer Automated Measurement and Control (CAMAC) and acts like a 24 megabit/second computer channel. CAMAC interface cabinets, or crates, are located at each of the dome simulators, the simulation control console, and the Manned Combat Station area. A Kinetics System highway driver provides a standard interface between the computer cluster and each crate. This interface allows for substituting another host computer or for adding other computers to the CAMAC network. Data travels from the source computer channel through the serial highway driver, across the fiber optic network to the addressed crate, through the serial crate controller to the crate backplane, and arrives at the memory of the addressed module. Any computer on the network can receive information from, or send information to, any interface device on the network. Standardized hardware interfaces to major components (e.g., throttles) were also developed so that components in various dome simulators and Manned Combat Stations would be plug compatible for easy modification or exchange.

General Purpose Simulation Computers

The simulation facility uses several SEL/Gould/Encore (hereafter referred to simply as Encores) simulation computers as the backbone processing power for realtime simulation. The computers are inter-connected through reflective memory to provide a parallel processing simulation environment. Ethernet is used to communicate between the Encores and Silicon Graphics workstations, used as display generators for the manned simulators. Simulation software components are typically distributed around the computer cluster to optimize efficiency and throughput, as shown in Figure 4. This configuration also gives a great deal of flexibility to the facility as software is easily ported to the various computers and used in the realtime simulation.

Ethernet. Due to the availability of Ethernet on virtually all computing equipment, it was chosen as the standard interface mechanism between the Encore computer cluster and all external processors. While Ethernet is not normally associated with real-time

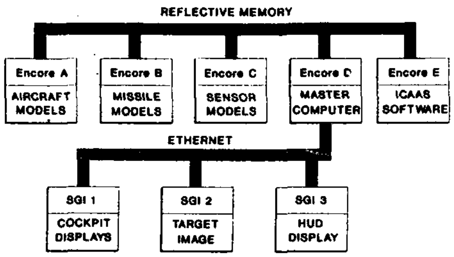

FIGURE 4. Distributed Architecture

operations, data rate analysis of the system determined that Ethernet's 10 Megabyte per second transfer rate could support the anticipated data traffic, provided that packet collisions on the bus could be minimized. In order to reduce bus traffic, special software drivers were developed for each of the computers. These drivers avoid the overhead of layered Ethernet protocols such as TCP/IP. By utilizing the bus at the low-level Ethernet 1.0 specification, all "hand-shaking" and error correction traffic was eliminated. During realtime simulation operation, a lost frame of data is considerably less important than maintaining constant throughput.

Shared Memory. While Ethernet provides the mechanism for communicating with the non-Encore processors, inter-processor communications within the Encore computer cluster require much higher data rates. Multi-ported memories are used to connect the nine Encore computers in the cluster. High-speed shared memory and reflective memory subsystems are used to meet this requirement. Memory partitions are set up for simultaneous access on all processors.

Graphics Computers

The facility has fourteen Silicon Graphics workstations to generate dome cockpit head-down displays, head-up displays, target images, MCS displays, and test set-up and monitoring displays such as the Battle Perspective Display, described below. In addition, a stroke graphics computer is used to generate symbology for the Agile Eye helmet mounted display. A General Electric Compuscene IVa image generator is used to provide the out-the-window video in the dome simulators. All the graphic computers communicate to each other, as well as to the Encores, through the Ethernet network described earlier.

Battle Perspective Display. The Battle Perspective Display provides a realtime view of the combat airspace from any viewing angle. The display consists of a grid representing the ground, which can be traversed via a flexible input mechanism (mouse inputs, menu selections, and/or keyboard interaction). The input mechanism supports both ground and elevation translations, as well as rotations about the x,y,z axes. Aircraft are displayed on the grid with corresponding aircraft ID, altitude, trailing vector, and ground track. The trailing vector displays the last six seconds of the flight path. Missile trajectories are also displayed. Figure 5 illustrates the BPD for a sample air combat run.

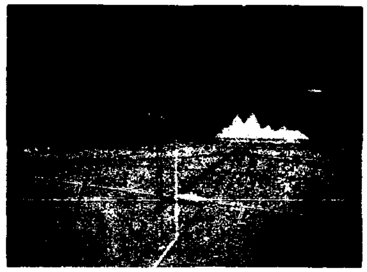

FIGURE 5. Battle Perspective Display

The BPD provides the test director with a variety of information window options. The Status window displays information on each aircraft, including aircraft ID, altitude, heading, Mach number, airspeed, and angle-of-attack. The Relative Data window displays information about two selected aircraft such as range, bearing, and aspect angle. The Plane View option provides an out-the-window view from any selected aircraft. Other options include zoom, decluttering, and scenario replay.

Air Combat Software

To provide the basic capability of intelligent digital threats, the Air-to-Air System Performance Model (AASPEM) analysis tool was extensively modified to execute in realtime and accommodate pilot-in-the-loop players. The primary goal of the air combat simulation software development was to provide a flexible mission simulation architecture that could be quickly adapted for the hardware and software requirements of individual programs. The simulation environment is used by a variety of programs for analysis activities ranging from total mission analysis to detailed performance analysis of a single aircraft subsystem. In order to provide the degree of support required throughout the 1990s, three major features were incorporated in FDD modified AASPEM. First, a modular software structure with standardized interfaces for each type of simulation component (e.g., aircraft, weapon, or sensor model) was established. Second, the modular software structure was combined with a distributed software architecture that provides a simulation engineer with the capability to quickly map simulation software components onto specific hardware processors. Finally, a distributed heterogeneous hardware architecture was established that allows for mixing a variety of processors and piloted simulators to meet the needs of many different simulation programs (Reference 3).

The key to providing an extremely flexible mission simulation was to develop a modularized software structure. In the original AASPEM code, all simulation components are linked together in one

batch process. Due to the constraints of realtime processing and the need to interchange simulation model components, many of the components had to be separated from the core software and rehosted as processes external to the main core. Therefore the original AASPEM software was restructured to partition the software into logically connected simulation components. This modular structure allows for quickly constructing a custom simulation from "building block" modules. For each component type, a standard interface was developed and tested. Program specific components under research can be quickly interfaced to the simulation executive via these standardized interfaces. This structure allows the simulation engineer to use standard simulation components for the majority of the simulation system, and use custom-developed models to satisfy specific program requirements. Simulation development efforts can then be focused upon the particular system or mission phase to be studied. During the air combat simulation development, standardized interfaces were developed for the following simulation components: aircraft models, weapons models (missiles and guns), sensor models, and piloted simulator input/output. The definition of these standardized interfaces includes all of the information that is required from the specific test component to drive other simulation components, as well as the information from the air combat simulation that may be required by the test component. Simulation components that were available in the original AASPEM software were restructured to communicate via these standardized interfaces.

IV. HOSTING THE ICAAS SOFTWARE

The most significant challenge facing the government ICAAS simulation program was hosting the ICAAS software on the simulation facility's general purpose computers since the software was designed to execute on a specific flight worthy computer architecture.

ICAAS Flight Test Configuration

The ICAAS flight test aircraft utilizes a modified F-15E avionics bus architecture. All the ICAAS specific software resides on the ICAAS Integration Computer (IIC) or the ICAAS Support Computer (ISC). The two computers are identical and consist of three MIPS Incorporated R3000 micro-processors and three R3010 co-processors. The operating system supports inter-processor communication, realtime multi-tasking, and allows for internal synchronous and asynchronous operation. The IIC and ISC use an Inter-ACT Ada compiler and have a throughput of 12 to 15 million instructions per second. The ACFMS software resides on the IIC while the ISC hosts the IAM, IFFC, and ACES software.

ICAAS Flight Test Software. Figure 6 illustrates the breakdown of the ICAAS software on the IIC and ISC computers. The functionality of the ISC software

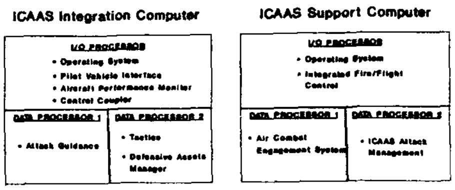

FIGURE 6. Flight Test Software Configuration

requires a basic synchronous implementation. However, the functionality of the ACFMS software requires an event driven architecture. A brief description of this architecture is provided so the reader will understand the complexity of the ACFMS software. Figure 7 best illustrates the synchronous and asynchronous processing requirements of the ACFMS software, using an adaptation of the Design Aids for Real Time Systems (DARTS) method. Figure 8 provides a description of the DARTS symbols used in Figure 7. The ten ACFMS processes are represented by the circular symbols. The scheduling of all the processes is on a priority basis. The PVII System Control, PVII Flight Plan Control, Control Coupler, APM, DAM Multiple Missile Track Algorithm, and DAM Control Coupler processes are interrupt driven. The Flight Path Management and Tactics processes are event driven and are blocked on the Rebuild Flight Plan and Tactics Algorithm Queue respectively, until a message is received. The Trajectory Generation and Control process is activated when required. The other queues and event flags on the DARTS chart are a means to assure messages are not lost during inter-process and inter-processor communication.

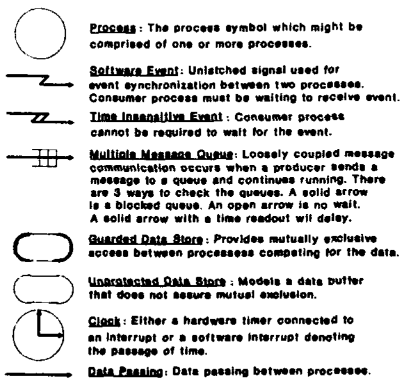

FIGURE 8. DARTS Chart Symbol Definition

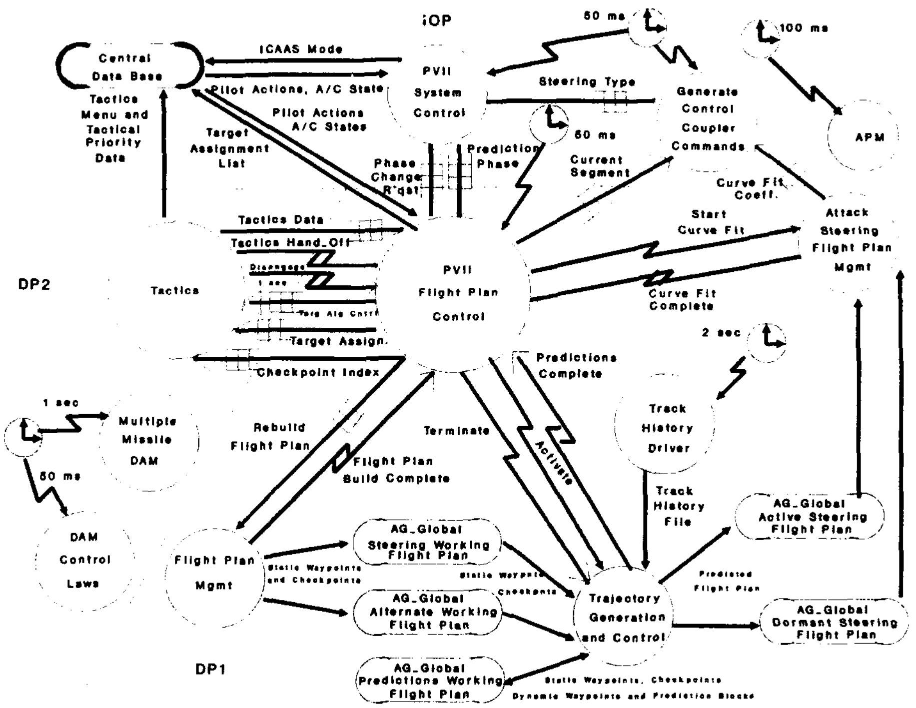

FIGURE 7. Flight Test Darts Chart

ICAAS Simulation Software Configuration

The government ICAAS simulation will verify the test results of the contractor ICAAS simulation. The government ICAAS full mission simulation configuration is shown in Figure 9. The ICAAS simulation configuration contains the piloted and digital test environment software, the ICAAS Ada software, and graphic display generation software.

ICAAS Simulation Software. The integration of the ICAAS system software onto the general purpose computers required making enhancements to the standard Encore MPX operating system. The operating system enhancements were necessary to implement the ACFMS message passing queue structures. Due to the portability of the Ada software, modifications to the application software were minimized. The only major change involved modifying the ICAAS 1553B bus software to use the Encore reflective memory. The 36 megabytes per second performance of the Encore reflective memory simplified the integration of the software by eliminating the need to pack data into a 1553 bus. The ICAAS lead and wingman aircraft both require an Encore 2040 to simulate the ACFMS software. The ICAAS IAM software requires a two-processor Gould 9780 for both ICAAS aircraft.

The DARTS chart in Figure 10 is the FDD simulation equivalent to the flight test configuration DARTS chart in Figure 7. It is used to describe the overall simulation synchronization, excluding the display processors. The master scheduler process is the only process tied to the realtime clock. The slave scheduler processes are activated by the master scheduler or other slave schedulers using software interrupts. The synchronization of the software is accomplished by activating and blocking the scheduler processes at the appropriate time. The master and slave schedulers are generic software routines which allow the user to schedule software modules on any processor. The software realtime schedule is easily changed using menu driven routines between simulation runs. Menu driven routines are also available to modify the simulation scenarios.

The implementation of the ISC and IIC Central Data Bases (CDB) also required modifications. The flight test ISC and IIC computers require memory mapping of each CDB object. However, the simulation software defines reflective memory partitions using the Encore Ada system service package. A record of the CDB objects is defined in the CDB package and this record is attached to the memory partition during program elaboration. This not only provides inter-process and

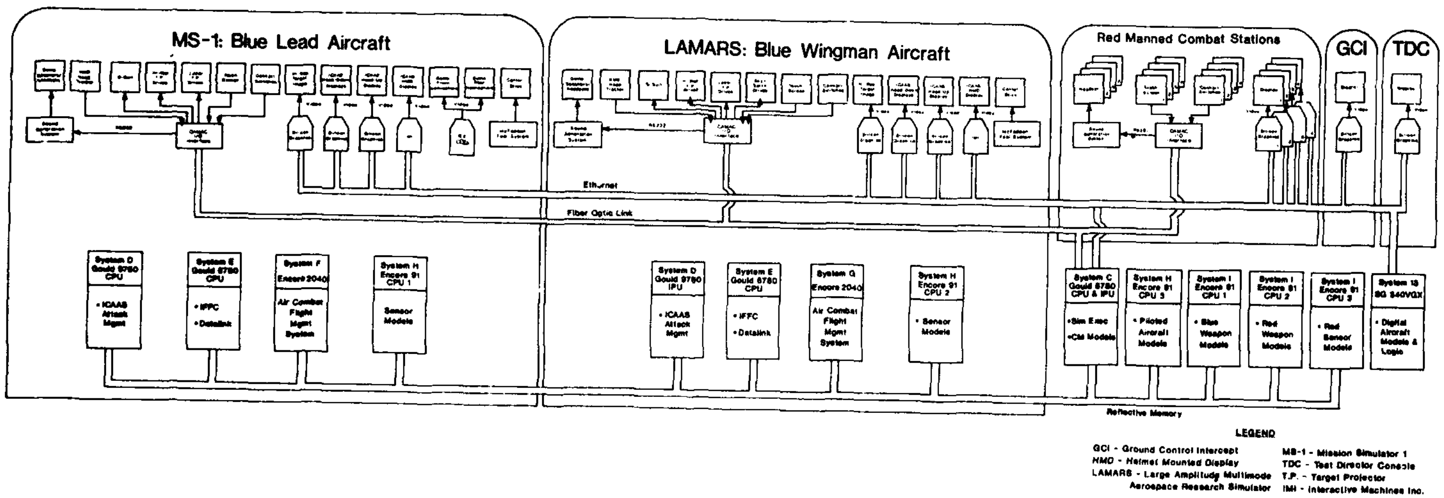

FIGURE 9. FDD ICAAS Simulation Configuration

processor communication, but also enables the user to easily monitor the CBD objects through a menu driven parameter display.

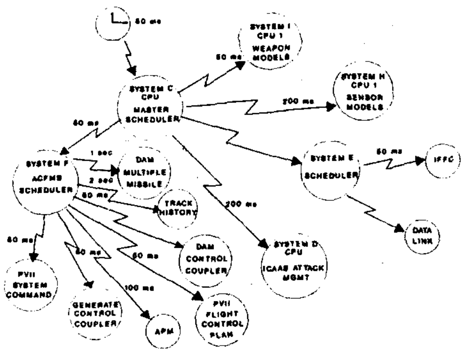

FIGURE 10. FDD Simulation Foreground Scheduling DARTS Chart

Piloted Simulator Software. The FORTRAN piloted simulation test environment consists of high-fidelity aircraft, missile, gun, sensor, chaff, and flares models, as well as the software to drive the simulator components such as target projectors, g-suits, etc. This software is hosted on an Encore 9100 computer which consists of three 88000 Motorola micro-processors. The Encore 91 is also connected to reflective memory to facilitate communication between the ICAAS Ada software and the FORTRAN memory partitions. The only test environment software modules not written in FORTRAN are the ICAAS sensor models, which are part of the Ada software developed for ICAAS by the contractor. In order to give the pilots acceptable flying qualities, each of the piloted simulators has a high-fidelity, six degree-of-freedom aircraft model. A number of different Blue and Red aircraft models are available. The missile models are five degree-of-freedom flyout models which can be run at a 40HZ update rate. This frame rate allows precise missile end-game modeling. Several Blue and Red state-of-the-art missile models are also available.

Digital Player Software. The digital players are provided by the standard air combat software package based on AASPEM, as described earlier. For the ICAAS scenarios, the software package provides the bombers, AWACS, and threat wingman aircraft. The digital wingman are each assigned to a MCS simulator and fly cooperatively with that manned player. In this way, each digital wingman has the benefit of its intelligent, piloted lead aircraft. The digital bombers fly a pre-programmed penetration path to a target. If attacked, they will respond by putting the attacker on their beam and dis-engaging. AWACS aircraft fly a fixed Combat Air Patrol position unless threatened.

V. ICAAS SIMULATION TESTING

Objective

The objective of the ICAAS ground-based simulation at the Flight Dynamics Directorate is two-fold. First is to verify the simulation results obtained at the contractor facility by repeating the test matrix under as close to identical conditions as possible. The second major objective is to expand the contractor test matrix by looking at different force ratios, scenario initial conditions, threat aircraft and weapon types, and simulator configurations. In addition, the simulation will be available as a technology transition tool to permit a large number of USAF pilots to get hands-on exposure to ICAAS.

Approach

Three basic missions are defined for the ICAAS system study: base defense, AWACS defense, and bomber escort. For each of these missions, there will be two ICAAS aircraft comprising the Blue fighter force. Up to eight fighters will comprise the Red force. In addition to the fighters, bombers and other noncombatant aircraft are included in the scenarios. In particular, Blue aircraft not directly involved in the briefed ICAAS mission are inserted into the scenario airspace to evaluate the friend or foe identification features of ICAAS. Figure 11 depicts representative initial conditions for the base defense mission. Two complete ICAAS systems are hosted at the FDD facility.

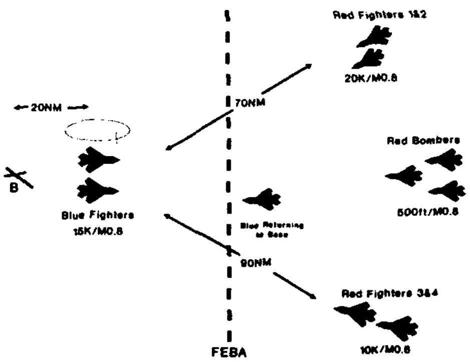

FIGURE 11. Airbase Defense Mission Initial Conditions

The first is for the lead ICAAS pilot flying in the MS-1 simulator. The second is for the wingman ICAAS pilot flying from the LAMARS simulator. The intra-flight data link is simulated connecting the two ICAAS aircraft. The ICAAS aircraft will be equipped with an advanced sensor suite consisting of an Electronically Steered Antenna (ESA) radar, an Infrared Search and Track (IRST) system, missile warning system, and an advanced electronic warfare and self-protection system. Up to four of the Red aircraft will be flown from the

MCSs; the remaining Red aircraft will be flown by the computer using AASPEM pilot decision logic. All bombers, whether Blue or Red, will be computer controlled.

Due to the large number of advanced technologies on-board the ICAAS aircraft, improvement in overall tactical effectiveness could be due to a number of different factors. The test matrix is designed to isolate the effects of the advanced sensor suite, advanced pilot-vehicle interface, sensor management and fire control in the IAM, flight and attack management in the ACFMS, low observables, and intra-flight datalink. Starting with the baseline aircraft with standard sensors and PVI, each new technology area will be added and the tactical performance increase measured. Thus the contribution of the advanced ESA radar with an AIM-120 will be measured, then the IAM will be added to determine the effects of computer-controlled sensors, track correlation, and fire control, etc. Finally the full ICAAS system as described earlier will be used. This will result in a ranking of which technologies contribute the most to increased fighter effectiveness.

The Blue and Red pilot teams will separately plan and brief their respective missions and decide on overall tactics, commit criteria, disengagement criteria, etc. Simulation test runs will typically begin with the defending aircraft in a Combat Air Patrol (CAP) and the threat aircraft outside of sensor range. The size of each force, as well as the number of digital versus manned players will be not be known by the opposing Blue and Red teams. The ICAAS players are autonomous with no AWACS or Ground Control Intercept (GCI) support. The Red team will have GCI support when operating on the Red side of the forward edge of battle area (FEBA). Simulation runs will continue until all fighters are killed or disengage. Therefore, the missions will progress through BVR to merge and finally close-in combat, if necessary.

Data Collection and Analysis

Measures of Effectiveness (MOE) and Measures of Performance (MOP) are used to directly interpret the simulation results in terms of the test objectives. The MOEs are designed to measure the mission level effectiveness of the ICAAS system. The MOPs measure specific ICAAS system performance. The data needed to generate the MOEs and MOPs are collected from debriefings, questionnaires, and simulation computer systems. Six primary areas will be examined to measure system performance: mission success, engagement success, situation awareness, decisions, degree of covertness, and workload. Each of these areas will be described in more detail below. The types of data collected are similar to that collected at the contractor facility to allow the comparison of results.

Mission Success. A separate Measure of Effectiveness is being used for each mission scenario type to objectively measure the success of the mission. For the AWACS support mission, the MOE is:

AWACS Defense MOE = -0.6*(LRA/TRA) - 0.4*(KBF/TBF)

For the bomber escort mission, the MOE is:

Bomber Escort MOE = 0.1*(KRF/TRF) - [0.2*(KBF/TBF) - 0.7*(LBA/TBA)]

And, for the base defense mission, the MOE is:

Base Defense MOE = [0.1*(KRF/TRF) - 0.7*(LRA/TRA)] - 0.2*(KBF/TBF)]

Where: LRA = Leaked Red Attackers
TRA = Total Red Attackers
KBF = Killed Blue Fighters
TBF = Total Blue Fighters
KRF = Killed Red Fighters
TRF = Total Red Fighters
LBA = Leaked Blue Attackers
TBA = Total Blue Attackers

The weighting constants multiplying each term of the MOEs indicate the relative importance of that term to the mission success. The numerical range of these three MOEs is 1.0. For example, the best MOE value for bomber escort is 0.8; the worst MOE value is -0.2. The ICAAS program goal is to show an incremental improvement in each of these MOEs of at least 0.25 when comparing baseline, non-ICAAS equipped aircraft with the same aircraft equipped with ICAAS features. In addition to these MOEs, the number of bombers on target and AWACS survival will be used as a measure of mission success.

Engagement Success. Engagement success will be evaluated by examining a number of Measures of Performance. Typical MOPs are kills, losses, and fratricide by weapon type, number of leaked attackers, percent aircraft fired at by type, and percent of losses not caused by weapon kills.

Situation Awareness. Situation awareness will be determined through objective and subjective means. A pilot questionnaire will allow the pilot to subjectively rate the ICAAS system and relate how much situational awareness he thought he had. Several MOPs provide objective data to gauge situation awareness, such as proportion of Red forces detected over range and time, percent of missiles double targeted, number of hostile IDs before preferred launch range, and total time within threat missile intercept zone.

Decisions. By examining pilot decisions, it will be determined how much the ICAAS system aided the pilot in making timely and effective tactical decisions. Representative MOPs examined will be percent of valid missile shots prior to first valid enemy missile shot, percent of Red aircraft simultaneously engaged by more than one Blue fighter, time from initial target detection to commit, weapon usage by type relative to RMAX and RNE, F-poles, fuel usage, tactic selected, and disengagement time.

Degree of Covertness. By isolating this area, the impact of a non-ICAAS low observable aircraft versus an ICAAS-equipped low observable aircraft will be analyzed. The MOP to be used is the number and percent of Blue forces detected and targeted.

Workload. Workload is measured through subjective means using the Subjective Workload Assessment Technique (SWAT) rating system. Under this system, the pilot is asked to quantify the mental workload required to complete specific tasks. The workload consists of a combination of three dimensions: time load, mental effort load, and psychological stress load. The pilots rate each dimension individually on a scale from one to three. These numbers are then weighted by pretest rankings completed by the individual pilots to account for differences in perceived workload. A normalized score is then produced which rates the total workload on a scale from zero to one hundred, zero being the minimum and one hundred being the maximum.

Data will be collected both in realtime and post-processing formats. During the simulation runs, each pilot's displays (head-down, head-up, and helmet-mounted for the MS-1 and LAMARS; head-down for the four MCSs) as well as over-the-shoulder views of the pilots in the simulator cockpits will be monitored at a central control console. In this way, pilot actions can be observed and cursory performance and worload data can be collected. Three channels of video and audio can be recorded for later viewing. At a minimum, both ICAAS aircraft head-down displays will be video taped since much of the data needed can be derived from these displays. In addition, the aircraft and missile data which drives the Battle Perspective Display will be stored on computer disk. Then, at a later time, the entire scenario run can be replayed in the BPD format allowing the pilots and test directors to re-examine the air battle exactly as it took place, from any perspective and at various playback speeds.

Pilot questionnaires will be used after each simulation run and after the entire simulation session to collect subjective data on situation awareness, workload, and performance/acceptance of the ICAAS system. To ease filling-out each end-of-run questionnaire, the forms will be programmed on the graphics computer and presented to the pilot on the cockpit front panel monitor. Then, using the touch screen interface, the pilot can select his responses to the questions. The data can be printed-out at a later time.

At the beginning of each simulation run, a computer file is created which describes the initial conditions and mission profile of the particular run. An example is shown in Table I. Other 'quick-look' data will be available in printed format after each run at the simulation control console, as shown in Table II. This data will be used to help verify the validity of each simulation run and to provide confidence that the test matrix is isolating the appropriate parameters. Possible reasons for an invalid run are the pilot encountering unrealistic flight conditions (e.g. excessive g forces), defying rules-of-engagement, or not following briefed mission profile. In addition, this data will assist the pilots during the mission debrief and while playing back the Battle Perspective Display. Finally, a complete event ledger and select time history data will be collected during each simulation run and stored on computer disk or tape for later analysis. A sample of the event ledger data is shown in Table III, the time history data in Table IV. By using the information available in Tables I through IV, the videotapes, and the BPD playback feature, each simulation run can be completely re-generated and analyzed in detail. Furthermore, analysis packages can be used to statistically examine the data which has been stored in computer files and generate the Measures of Performance.

VI. CONCLUSIONS

The USAF Flight Dynamics Directorate has a flexible air combat simulation facility which allows new technologies to be quickly inserted in the environment and their tactical impact evaluated. The first program to use this capability is the ICAAS program which represents a leap in flight and attack management aid to the pilot. Carefully chosen measures of performance and effectiveness will be used to isolate and assess the various features of ICAAS. The government simulation will be used to verify the contractor's ground-based simulation results.

The flexibility of the simulation design allows a wide range of technologies to be tested while they are still in the research and development stage of development. The research community and operational fighter pilots get a concrete assessment of the tactical payoff of a given new technology before the expense and risk of flight testing.

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2. Halski, Donald J. and others, "Integrated Control and Avionics for Air Superiority: A Knowledge-Based Decision-Aiding System", *in* AGARD CP No.474, September 1990, Paper 53.

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TABLE I
SIMULATION RUN INITIAL CONDITIONS

AIRCRAFT (For each Blue & Red)	Mission List (For each Blue & Red)
Position	Mission Type
Airspeed	ROE
Heading	Bullseye Location
Fuel Load	FEBA Location
Weapons Load	Desired Engagement Zone Location
CM Dispensables Load	Bomber Waypoints
Sensors	
ICAAS Mode	
Simulator Station or Digital	

Table II
End-of-Run Simulation Summary Data

Run Number	Date	Pilot	Mission Length
23	02/17/92	Caudill	16.25 min

Run Valid: NO, A/C 1 exceeded g limit

Mission Type & Force Size
AWACS Defense 2v4

ICAAS Aircraft Configuration
ADV166, ICAAS ON, LO

Blue Fighters Killed: 1
A/C 2 - AA-10c

Blue Bombers/AWACS Killed: 0

Red Fighters Killed: 2
A/C 5 - AIM-120
A/C 6 - Ground impact

Red Bombers/AWACS Killed: N/A

Leaked Blue Attackers: N/A

Leaked Red Attackers: 0

MOE: -0.2 (0.0 -1.0)

Blue Force Exchange Ratio: 2.0 Red Force Exchange Ratio: 0.5

Targeting Data

# Reds tracked by Blues:	2
# Reds assigned by Blues:	2
# Reds launched on by Blues:	2
# Reds launching missiles:	1
# Blues tracked by Reds:	2
# Blues assigned by Reds:	1
# Blues launched on by Reds:	1
# Blues launching missiles:	2

Weapon Summary
13.50: A/C 1 launched AIM-120 at A/C 5 at .63RMAX; PK .75 KILL
14.05: A/C 2 launched AIM-120 at A/C 6 at .80RMAX; Exc Flt Time
15.50: A/C 6 launched AA-10c at A/C 2 at .59RMAX; PK .87 KILL
16.10: A/C 1 launched AIM-9M at A/C 6 at .85RMAX; IR SIG L

Total Time Within MIZ: 5.05 min

Total Time Within Datalink: 15.50 min

Total Time in ICAAS Modes

	A/C 1		A/C 2
Tactics:	3.75 min	Tactics:	3.67 min
Attack Guidance:	10.05 min	Attack Guidance:	9.80 min
DAM:	0.0 min	DAM:	0.75 min
GCAS:	0.90 min	GCAS:	0.0 min
MCAS:	0.0 min	MCAS:	0.0 min

TABLE III
EVENT LEDGER

WEAPON EVENTS

Radar or IR lock-on/break lock
For each weapon launch:
- Weapon Type
- Launching A/C ID, Altitude, Mach, Gee
- Target A/C ID, Altitude, Mach, Gee
- Target Bearing (Az & El) from Launcher
- Target Range at Launch
- % RMAX at Launch
- % RNE at Launch
- Missile Time-of-Flight
- AMRAAM Time-To-Autonomous
- Target Aspect Angle at Launch
- F-Pole
- PK & Kill Flag
- Reason for Miss, if Miss
- Target Gee, Roll Acceleration at Intercept

TRACK/ID DATA

Track File Started (or Dropped) By: (Aircraft ID) on (Aircraft ID); Elapsed Time: (Secs); Range: (NM)

Identification of (Aircraft ID) By: (Aircraft ID);
Elapsed Time: (Secs); Range: (NM);
Sensors Contributing: (Radar, IRST, Optical)

ICAAS EVENTS

Start Times in Tactics, Attack Guidance, DAM, or APM Modules
For each event: Elapsed time, Range to Target Centroid,
Range to Primary Designated Target, Tactics
Figure-of-Merit
Data Link Break/Rejoin

Other Events

Aircraft out of Fuel
Ground or Mid-Air Impacts

TABLE IV
TIME HISTORY DATA

Run Identification Data
Aircraft State Vector (inertial position, velocity, attitude)
(body velocities, accelerations)
Air-to-Air Missile State Vector
Missile Launch Envelope Data
Gun Fire Control Data
Sensor Status (mode, pointing angles, search volume)
Target Track Files
Pilot Inputs
ICAAS Tactical Plan Parameters
ICAAS Control Coupler Data
ICAAS Threat Missile Evasion (DAM) Data
ICAAS Hazard Monitoring Data
ICAAS Energy Maneuverability Data

The Evaluation of Simulator Effectiveness for the Training of High Speed, Low Level, Tactical Flight Operations

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1. SUMMARY

The German Government has initiated a three phase program to evaluate the use of an improved simulator for the Tornado aircraft. In the first phase of this program CAE has built a prototype simulator, referred to as the Evaluation Unit (EU). The improvements in the EU consist of visual system upgrades to provide a CAE Fibre-Optic Helmet Mounted Display (FOHMD) for the pilot and weapon system officer (WSO), with imagery from an Evans & Sutherland ESIG-1000 image generator, as well as a six-degrees of freedom (DOF) motion system. The EU has been installed at CAE Electronics GmbH in Stolberg, Germany. Military and industrial representatives are conducting an evaluation, under responsibility to Bundesamt für Wehrtechnik und Beschaffung (BWB), of the upgraded simulator to assess its capability to provide high speed, low level, tactical flight operations training capability. A factorial analysis of variance (ANOVA) design is being used to assess objectively recorded performance data and subjective impressions data collected during simulator flights by military crews from the German Air Force and Navy.

2. INTRODUCTION

The mission of the Tornado aircraft requires low altitude, high speed penetration behind enemy lines. Maintaining mission preparedness is critical to NATO's readiness strategy. German reunification and other recent changes in the political environment have modified public perceptions concerning the acceptability of environmental and safety risks associated with aircraft operations over Germany's heavily populated land area. These considerations have led to increasing restrictions on such operations, compounding the difficulty of maintaining mission preparedness.

Public safety and environmental concerns about low-level flights in Europe have led NATO commanders to consider increased use of simulation to prepare crews to obtain maximum benefit from available flight hours. Although simulators have been used extensively, systems for low altitude, high speed flying have not been widely accepted. Flight crews and training personnel are understandably very demanding concerning the visual environment in any simulation of low-level operations. The original design of the Tornado Operational Flight and Tactics Simulator, (OFTS), visual system was not intended to support low-level operations.

Low-level flight challenges Tornado crews to deal with and respond to the flow of visual information rushing below the aircraft in the low/fast mission. The German Tornado crews must use the out-the-window view, along with radar, to identify visual cues for navigation and target orientation. To avoid being seen by hostile radar, they use terrain following and terrain masking. These techniques place a heavy workload on the crews.

Current peacetime altitude restrictions on flights over Germany severely limit opportunities to practice at the lowest desirable levels. For most crews, the only real opportunity to experience flight at these levels occurs during brief and infrequent training outside Europe, over terrain that does not represent conditions that may be encountered in actual missions.

This paper describes a program initiated by the German Government to address the problem of low-level flight operations training. The program is evaluating the contributions to low-level operations training made possible by simulator visual and motion system upgrades integrated into the Tornado OFTS. The first part of the paper addresses issues concerned with the hardware and software upgrades. This consists of a CAE FOHMD for the pilot and WSO, with imagery from an Evans & Sutherland ESIG-1000 image generator, as well as a six-degrees of freedom motion system. The second part of the paper addresses the design and data collection for an experimental study to evaluate the capability of the improved simulator in the training of low-level operations.

3. THE SIMULATOR UPGRADE

The upgraded Tornado simulator is a mix of several elements

some new and some which form part of the configurations of the seven fielded simulators. It was this mix of new and old and the availability of a Flight Simulator Development Rig, used by CAE Electronics GMBH to support simulator upgrades, which allowed the Phase One EU to be produced in a time frame which met the needs of the customer. The elements of the simulator which correspond to the fielded devices are the basic computer system, cockpit and cockpit interface, instructor station and Digital Radar Land Mass (DRLMS). The new elements are the FOHMD, Image Generator (IG), Motion System, Data Recording System and Air Target System.

3.1 Basic Simulator Changes

While the basic simulator is essentially the same as the fielded devices a number of changes were made to enable the system to support the new elements. The most significant change was that made to the frame rate of the core device. In the fielded simulators this is 18.5 Hz, 60 Hz in the EU.

The change to the higher frame rate was seen as imperative in order to achieve acceptable transport delay in the critical area of visual response to control input. To meet this requirement higher performance processors were substituted for the original Texas Instruments TI 980s. The new processors were still 16-bit machines and were thus not considered an ideal solution for the longer term, however they were readily available and had been previously used during simulator upgrades. Apart from the increase in computation rate the flight and control system models remained as in the fielded simulators and indeed the simulator was tested to ensure that handling characteristics were as before.

Changes were made to the interface subroutines to allow communication with the new IG, FOHMD system and new motion system and to support the transfer of data needed for analysis of mission performance. The instructor station was also modified to include new control pages for the added systems and to improve the management of the execution of the planned evaluation missions.

3.2 New Elements

Of the new elements added to the EU the FOHMD was of most significance as it offered the potential for the upgrade of the fielded simulators without great changes to infrastructure elements such as buildings, etc. The technology is radical compared to traditional systems such as domes but offers key performance advantages in the areas of scene brightness and contrast, as well as being of lower overall cost.

The image generator was also considered to be a key element, though the system chosen was in training use elsewhere and the technical risk considered low. In fact the requirements set by the Tornado program, in terms of database development, proved more difficult to meet than expected, as did the mating of the IG with the display system.

3.2.1 FOHMD

The FOHMD is an area-of-interest display employing a unique concept, the system is worn by the user. It uses very large format, flexible, coherent bundle, fibre optic cables to transfer images from projector assemblies to a helmet mounted optical system which presents the image to the user. It provides the wearer with a bright (up to 50 ft lamberts), high contrast scene (50 to 1 contrast ratio) over an instantaneous field of view of 127 deg horizontally and 66 deg vertically. The system is head and eye tracked, using infra-red optical trackers, to allow the image being presented to the wearer to reflect his direction of regard. Figure 1 illustrates the FOHMD concept.

The image presented to each crew member is formed, on Tornado, by three separate image generator channels. Two of these channels are used to generate left and right eye 'background' fields covering 88 degrees horizontally and 66 degrees vertically. The helmet display system overlaps these backgrounds to produce the overall field of view defined above. The background fields are of relatively low resolution, approximately 5 arc minutes per IG pixel, not sufficient to support the training tasks should they be used alone. However the FOHMD uses the third IG channel to generate a high resolution inset within the display which covers an area of approximately 24 degrees by 19 degrees with a resolution of approximately 1.5 arc minutes per IG pixel, as illustrated in Figure 2. Each eye uses two General Electric light valve projectors, one to provide the background image and the other to provide the inset image. These two images are combined together in the optical system to provide the composite scene observed by the wearer. The inset light valves for each eye share the same IG channel. On Tornado the inset region is eye slaved, so that the high resolution area follows the direction of regard of the wearer's eye.

The eye trackers are prototypes which were not originally intended to be included in the EU. However the initial testing indicated that eye tracking provided a net benefit to the system overall and as a result they were included for the customer evaluation. These prototype eye trackers exhibit some problems associated with alignment accuracy but have generally performed better than expected, considering the maturity of the system. The system's use of several independently monitored reflections and the 'dark pupil' concept employed have resulted in very few instances when the tracking of a subject's eye was not possible.

3.2.2 Image Generator (IG)

The IG is an ESIG 1000, with a total of seven separate channels, three each for the aircrew FOHMD's and one for an instructor station monitor. The two channels used for generating the high resolution inset fields on the helmets have a capacity of 2,000 polygons each and the background and instructor channels have a 1,200 polygon capacity. All channels generate 1 million pixels, except the instructor which provides 750,000.

Evaluation of Simulator for Training Low Level Operations

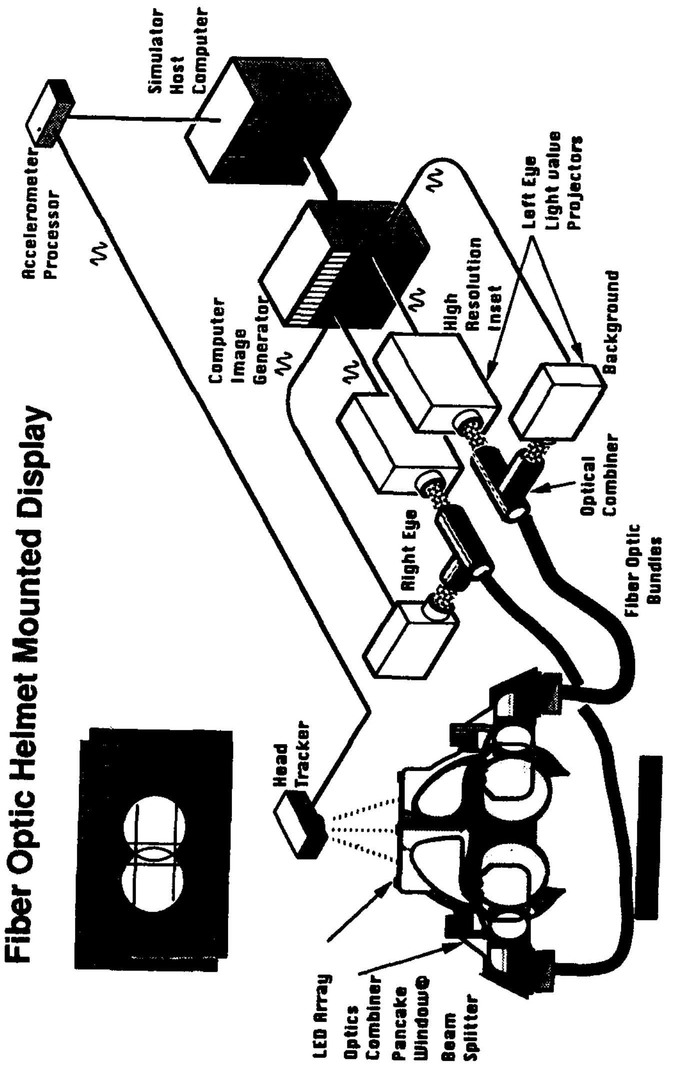

Figure 1 FOHMD System Configuration

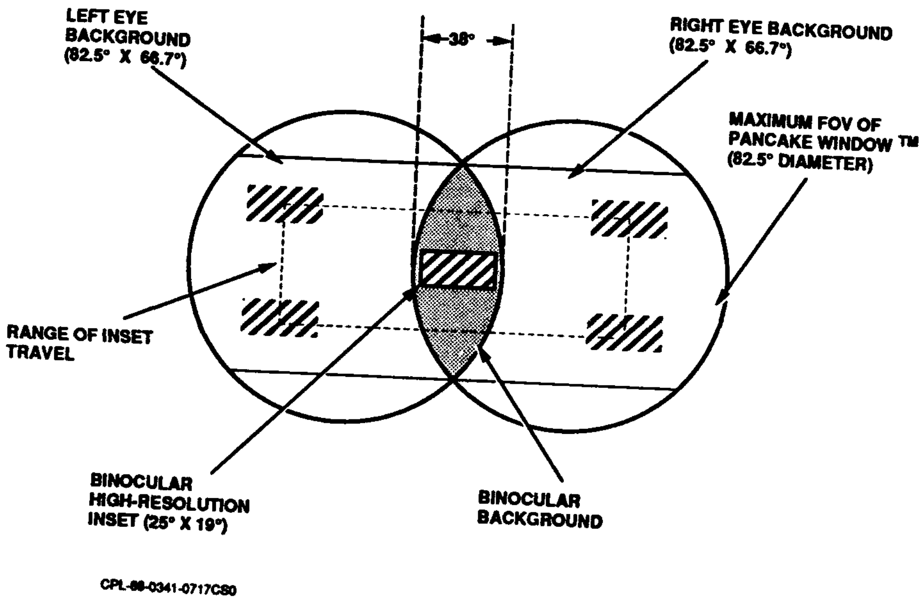

Figure 2 Helmet Display Configuration

This configuration was intended to provide maximum benefit when mated with the FOHMD with higher performance in the inset channel so that it matched the resolution capability of the optical system. In fact this arrangement did not provide the benefit expected, as all IG channels accessed the same data base and this was designed to prevent overload of the background channels. As a result the inset region of the display actually displays less polygons than the background, though each element is better resolved, ie. appears in better focus to the observer.

During the data base design it became apparent that this extra polygon capacity was difficult to exploit as the addition of extra scene elem nts in the inset channel, could only be achieved with extra levels of detail. Level of detail changes had to be arranged such that the scene observer was unaware of the change. Elements brought in too abruptly, 'popped' into view and were disturbing. To be effective in an area of interest system such as the FOHMD level of detail changes need to be independently controlled for inset and background regions such that features are observed sooner in the inset region than in the background. In the ESIG 1000 all level of detail changes are based on the same range dependency in all channels. Thus the extras provided in the inset amount to fine details such as windows, aircraft markings, etc., observable because of the higher resolution of the channel.

The ESIG 1000 makes extensive use of texture to provide scene detail and the simulation of farm fields, forest canopies, villages and towns. These textures provide significant benefit in terms of scene detail but considerable work was required to prevent aliasing of these textures when viewed through the helmet optics. Matching characteristics of IG and FOHMD in general proved difficult until a light valve was used to view the results of design work. Many elements of the data base had to be significantly revised before the final version, which fully exploits the available IG capacity, was produced.

As the FOHMD is worn by the user the picture, though collimated at infinity, is immediately in front of the viewers eyes and not, as in more conventional display systems, placed outside the cockpit. This characteristic results in the need to generate a visual model which represents the cockpit, referred to as a cockpit mask. The cockpit mask provides the correct occultation of the scene outside the aircraft and allows the wearer to see into the cockpit. The cockpit mask also provides a model of the canopy frames. The cockpit mask itself is placed inside a model of the aircraft so that when seated in the cockpit and wearing the helmet the user is presented with the illusion of being inside his aircraft complete with all the visible features as viewed from the cockpit. The FOHMD is thus unique in affording the trainees a view of own aircraft features such as wings, intakes, etc.

While this feature is unique it proved to be difficult to generate and position the mask in the IG and indeed difficult to gather the data necessary to support its development.

3.2.3 Motion System

The motion system added to the EU was a standard CAE 500 series digital motion system. The original Tornado simulators were initially intended to include a motion platform, so the development of the modifications necessary to incorporate one were fairly straightforward.

The mounting of the optical systems on a motion platform had not been previously attempted however, nor had the FOHMD ever been used with a g-seat/g-suit combination. Considerable design work and experimental testing were needed to design isolation platforms which would protect the sensitive projectors and optical assemblies from the effects of platform motion and vibrations. Figure 3 shows the general arrangement of the EU with the optical systems on the motion system. With these platforms installed the optical assemblies have shown no long term problems associated with the simulator motion and g-loading systems.

The simulator motion cuing system was optimised to gain the maximum benefit of both the motion platform and the g-suit/g-seat, in combination. Essentially the motion platform provides onset cuing and horizontal acceleration cues and the g-suit/g-seat sustained acceleration cues associated with hard maneuvering. The simulation of vibration cues due to aerodynamic buffet and the like was shared between the two systems. This process was complicated somewhat by the need to prevent visual system anomalies resulting from motion inputs. The bandwidth of the optical system is essentially limited by the total throughput delay of the system and it was known that certain motion frequencies were likely to excite out of phase oscillations in the viewed image. Care was required as a result in generating buffet cues to ensure that unwelcome effects were minimized. In the event the concern was largely unfounded as the required motion frequencies fell outside of the regions critical to the visual system.

For evaluation cases where the motion platform was not used, the original simulator g-suit/g-seat system and software models were employed.

3.2.4 Data Recording and Air Target System

While the originally fielded simulators provided data recording systems, they were not adequate to collect the large quantities of data necessary to support the planned evaluation. To satisfy this requirement the data recording was extended to include 100 separate variables recorded at up to 10 Hz during each evaluation mission.

An air target simulation was added, able to perform the roles of wingman or leader as required by the evaluation missions. This proved to be a very successful addition to the capabilities of the device. The computer controlled wingman can fly in close formation with the trainee aircraft as well as perform low level contour flying, so that it can as act as a leader to allow evaluation of the systems capability to support formation flying.

Evaluation of Simulator for Training Low Level Operations

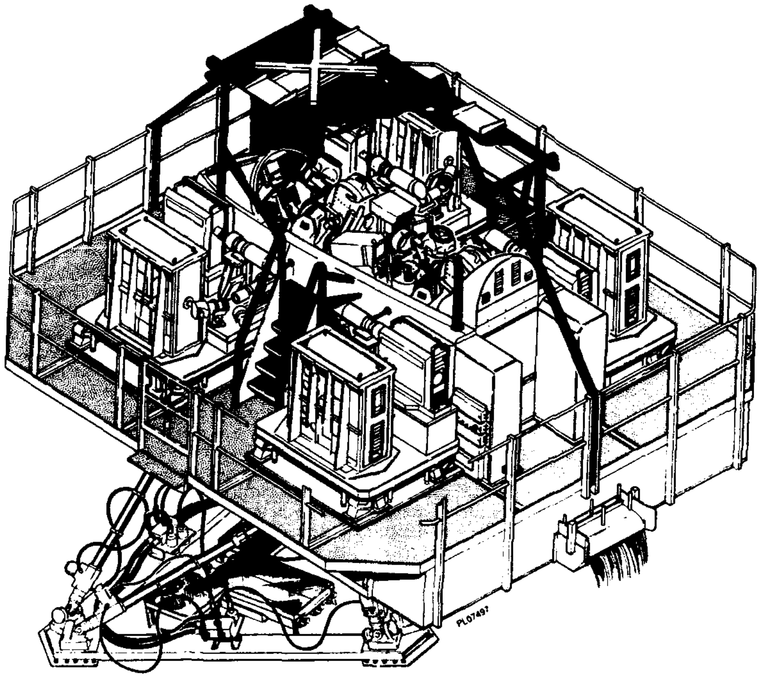

Figure 3 General Arrangement of Evaluation Unit

3.3 Issues

During the course of the development of the evaluation unit some of the original assumptions, as to the required performance, were called into question. Both CAE's own assessments and those of the customer upon his review of the device led to changes in the original goals. The decision to accelerate development of the eye-tracker was a result of crew feedback on head motion with the head slaved only system, as well as comment on the capability of the background scene. Cockpit illumination, fibre optic cable routing, cockpit mask design all relied heavily on the feedback given during the program by pilots and WSO's.

By the time the development was completed and the evaluation begun a great deal of information had been gathered with regard to overall system performance. The evaluation itself is of course still in progress and much more information will be produced. However the observations already made provide valuable data as to the directions development efforts should take.

The schedule for Phase One prevented these observations from affecting the configuration, except as previously discussed however, future systems will benefit much more. FOHMD development continues, aimed at providing improved image quality, comfort and a system which is more robust overall with less sensitivity to the set-up problems which have been observed with the EU system. Also any future upgraded OFTS will almost certainly include a modern computer system, with, in particular, far fewer interfaces than those present on the EU.

The development of the EU has brought into sharp focus the issue of matching display system and IG carefully so that the benefits of each can be maximized. Much of the information gathered during the development in this area came as a surprise for all concerned. However the lessons learned will certainly allow for more precise and beneficial matches to be made in the future.

4. EXPERIMENTAL EVALUATION

The evaluation of the upgraded Tornado simulator consists of several elements, as illustrated in Figure 4. The heart of the effort is an experimental study to assess simulator capability to train low-level operations, and to assess the subjective impressions of crews flying simulator missions designed to exercise the upgraded visual and motion features in simulation of low-level operations.

4.1 Analysis

As Figure 4 shows, the evaluation effort began with an analysis and design period, during which analysts interviewed several Tornado crews. The purpose of the interviews was to provide background information, establish a current training baseline, identify low-level operations tasks suitable for simulator missions, and help identify potential measures useful for assessing potential visual and motion upgrades to the simulator.

Members of 14 crews participated in the interviews. The interviewed crew members included a range of experience in flying hours and other areas. Specifically, the crews interviewed included:

- Five (5) Instructor Pilots
- Two (2) Pilots from NATO Tactical Leader Program (TLP)
- One (1) Simulator Instructor Pilot
- Four (4) Instructor WSOs (including some Weapons Instructors and an Electronic Warfare (EW) Staff Officer who served as Wing EW Officer)
- One (1) Squadron "#2"/Executive Officer (Navy Commander)
- One (1) Newly Designated WSO (just completed flight training)

The crews included representatives from Navy and Air Force bases. This diverse group provided a broad range of experience and outlook, and therefore offered an excellent sampling of interviews and opinions on the areas of interest addressed by the interviews.

During the interviews, the crews confirmed that peacetime restrictions on low-level flight operations make it difficult to train for wartime tactics, and that the simulator as originally designed cannot provide low-level operations training. The interviews provided hours of discussion of low-level flying and navigation, how these activities are performed, and the cues used by the crews in their performance. They identified the typical segments of a mission, and the tasks associated with the segments. The profile of a typical low-level mission consists of eight major segments:

1. Take-off	5. Attack
2. Transit	6. Egress
3. Penetration to Low Level	7. Recovery
4. Ingress	8. Penetration to Land.

Segments 3 - 6 are the portions of the mission in which the critical tasks associated with low-level operations occur. The interviews provided a focus on those segments, with an objective of identifying special goals or requirements specific to low-level operations. Such special goals or requirements lead to performance of maneuvers or procedures specific to low-level operations, or are especially constrained at low level, and are therefore likely to place heavy workloads on the crew. For these goals or requirements, associated low-level maneuvers or procedures judged as suitable candidates for inclusion in evaluation missions were reviewed for their dependency on visual and motion cues. This provided a basis for beginning to design evaluation missions.

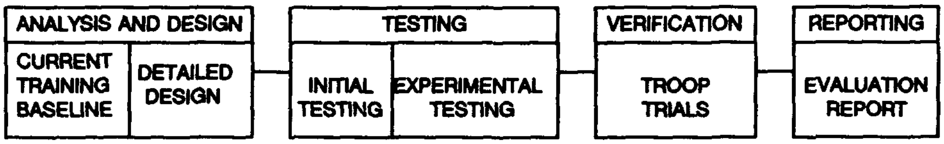

Figure 4. Elements of the evaluation for the upgraded Tornado simulator.

4.2 Design

For the evaluation, the upgraded simulator fortunately provides a means of systematically varying the cues provided by the visual and motion systems during performance of low-level tasks in simulator missions. Specifically, it is possible to vary the motion cues, permitting training either with a G-seat/G-suit system as on the originally designed simulator, or with that system augmented by the new 6-DOF motion base. Further, it is possible to obtain variations in the visual cues provided. This is possible because the visual data base for the evaluation contains certain areas, or corridors, with augmented cues. The data base represents an area in south central Germany, including urban areas and some primarily rural areas. Within these areas, the data base contains corridors in which visual detail has been augmented by hand-modelling of buildings and other urban features, or of natural terrain features. The scene also provides greater resolution of detail in the natural terrain corridors.

The capability for systematic variation in cues provided the basis for an experimental design in which crews practice low-level operations under different conditions. The basic concept is to have crews first fly a baseline test mission, then fly practice missions under one of the conditions, and finally fly a second test mission. Any observed differences between crews in performance in the second test mission can then be related to the conditions under which they practiced. Figure 5 illustrates this concept.

4.2.1 Missions and Measures

Missions were designed for the required test and practice sessions in the evaluation. The missions were constructed using information developed from analysis of the crew interview data. Low-level maneuvers and procedures that were considered likely to be sensitive to variation in visual or motion cues were sequenced to provide missions presenting realistic challenges to the crews.

Objective measures were assigned for collection during the missions. Although the evaluation simulator permits the automated recording, at a frequency of 10 Hz, of a large number of parameters, the focus for the experimental part of the evaluation is on a subset of measures selected to assess those differences in performance specifically related to the visual and motion upgrades to the simulator. Survey instruments were also developed to obtain crew subjective impressions of the simulation and specifically of the visual and motion cues presented during the missions.

To increase the realism, all segments typical of a low-level mission, including take-off and landing, were represented in each evaluation mission. Nevertheless, the focus of the objective data collection is on the segments requiring low-level operations. Measures taken during operations in these segments will permit a comprehensive evaluation of the contribution of the upgraded visual and motion simulation to performance of low-level operations in the simulator.

The test missions were designed to be very similar to each other. Nevertheless, they were constructed to require flight in slightly different areas of the data base to prevent the crews from performing by anticipating cues they had responded to previously. The practice missions each focus on different selected evaluation elements, but provide experience in low-level operations of the types required for the test missions.

Another short mission was developed to help crews adjust to the FOHMD during a brief familiarization ride to be conducted before the first test mission. The mission was designed to avoid low-level tasks while giving crews an opportunity to become familiar with the visual display before the baseline test mission.

4.2.2 Experimental Controls

The study design included a control for possible variation resulting from the slight differences between the first test mission and the second test mission. This control is to have half the crews fly one of the missions as their first test mission and the other half fly the other mission as their first test mission. The control also uses both missions during the test following the practice missions, but each crew receives the mission they did not fly previously.

The ability of the experimental design to detect significant differences will be strengthened if the crews in different simulator conditions of the experimental evaluation are approximately equal in terms of experience and ability. Therefore, a design goal is to assign crews to the experimental conditions, so that differences among the crews are balanced across the experimental conditions. This will increase the power of the statistical techniques that are used. It is a way to help ensure that any observed differences in performance

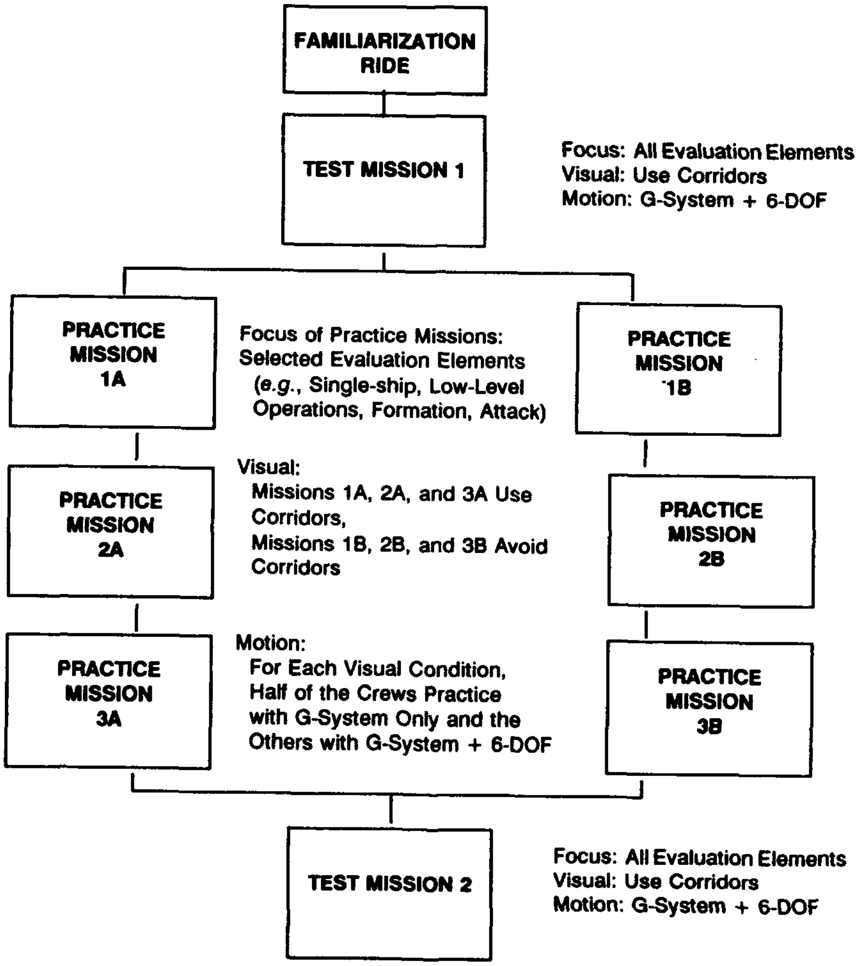

Figure 5. Types and Focus of Missions Experienced by Support Crews during the Experimental Evaluation.

and subjective impressions between the experimental conditions are a result of the visual or motion effects, rather than differences in crew characteristics.

The balance is achieved by matching the experimental groups for overall flight experience of the crews. The air wings providing crews for the experimental testing were requested to send crews in three experience categories based on the total number of flight hours: relatively inexperienced, experienced, and very experienced. The crews are assigned to experimental groups to equate the experience across the groups as closely as possible.

4.2.3 Statistical Design

Figure 6 shows the design in another way, to show the experimental groups and illustrate the statistical design for the experimental testing. It is a factorial design permitting statistical assessment using ANOVA or multivariate ANOVA (MANOVA) techniques.

The plan calls for a minimum of 40 crews to participate in the study. At Step 1, after a familiarization mission, all fly the first test mission. This mission exposes each crew to the full capabilities of the upgraded simulator, using the hand-modelled corridors in the visual data base and the 6-DOF motion system.

The 40 crews are then divided into the four experimental groups, matched for experience, for three practice missions under one of the experimental conditions established for Step 2. As the figure shows, there are two visual conditions, one of which uses the hand-modelled corridors of the visual data base and the other of which does not use them. There are two motion conditions, one using only the G-system and one using the 6-DOF motion platform. Simulator missions in condition A are flown with only the G-system motion cues and using the areas of the visual data base outside the hand-modelled corridors. Missions in condition B are flown with the G-system motion cues and using the hand-modelled corridors in the visual data base. Missions in condition C are flown using the motion system upgraded with the 6-DOF platform and areas of the visual data base outside the hand-modelled corridors. Missions in condition D are flown using the motion system upgraded with the 6-DOF motion platform and the hand-modelled corridors of the visual data base.

The design permits examination of performance and subjective impressions under the different conditions shown in step 2 of the figure. The design also permits observation of any *transfer* effects that remain from practice under those different conditions. This is possible because the design includes a Test Mission before the practice and a Test Mission after the practice.

5. CRITERION FOR JUDGING THE SIMULATOR

It may be argued that the ideal criterion for assessing simulator capability to provide training of high speed, low level, tactical flight operations is the aircraft. In an ideal experiment, performance in the aircraft would be the criterion, and Test Missions 1 and 2 would be flown in the aircraft, to determine if training under different simulator conditions transfers to performance in the aircraft.

Unfortunately, aircraft flights present challenges that make them undesirable as part of an experiment. First, peacetime restrictions on low-level operations in Germany make it impossible to perform the tasks (e.g., flight at lowest possible levels, terrain masking, weapons employment) that are necessary for the criterion measures. Second, the costs associated with the necessary criterion flights for 40 crews make it impractical to use aircraft flights. Finally, and most importantly for experimental validity, it is impossible to control the weather, wind conditions, and many other extraneous variables during actual flights; therefore, it is impossible to ensure that conditions are comparable between the first and second test missions, or between crews. Clearly, an alternative criterion is desirable.

The approach in the evaluation of the upgraded Tornado simulator is to use simulator missions under conditions employing the full features of the upgraded visual and motion systems as the criterion test missions. The logic for this criterion rests on three factors. First, the basic simulation model is an accepted faithful representation of aircraft performance. Second, the full features of the upgrades have been integrated with the basic simulation model to provide the closest possible representation of the visual and motion cues of the aircraft in the simulator.

The third factor is dependent upon subjective data being collected during the evaluation itself. If the subjective crew impressions collected during the first and second test missions provide evidence that the full capabilities of the upgraded simulator reflect operations in the aircraft to some degree, then those missions can be used as a surrogate for the aircraft to that degree, and can serve as a kind of criterion.

Certainly, the results of the evaluation must be interpreted with extreme caution. However, there will be data on performance of many different low-level tasks and procedures during the evaluation. It will be possible to analyze patterns observed in the objective data, concerning changes in performance after practice under the different simulator conditions. It will be possible to correlate observed patterns with crew subjective impressions of simulator performance and the adequacy of visual and motion cues. Based on these analyses, it will be possible to derive meaningful conclusions to guide additional trials of the simulator.

5. CRITERION FOR JUDGING THE SIMULATOR (Cont'd)

As illustrated in Figure 4, the experimental testing is not the end of the evaluation effort. The conclusions drawn from the experimental testing will be used to guide additional testing by military training personnel during troop trials. These tests will serve to verify conclusions from the experimental data, and the entire evaluation program will form the basis for final reporting and recommendations concerning the role of upgraded simulator training for high speed, low level, tactical operations.

Step 1 - Test Mission 1

Step 2 - Three Practice Missions under Experimental Conditions

		Visual Simulation	
		5 Not Using Corridors	*Using Corridors*
Motion System	*G-System*	A	B
	6-DOF	C	D

Step 3 - Test Mission 2

Figure 6. Experimental Design.

HARRIER GR MK 5/7 MISSION SIMULATORS FOR THE ROYAL AIR FORCE

by

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SUMMARY
In 1985, in anticipation of the phased replacement of the Harrier GR Mk 3 by the Harrier GR Mk 5, the UK version of the AV8B, the UK Air Staff issued a requirement for two mission simulators capable of fulfilling a comprehensive pilot training and evaluation task. It identified the need for simulators which would provide a wide range of psycho-physical cues with accurate flight and systems simulation, integrated with a high resolution, wide field-of-view visual system compatible with the Harrier's operational roles and inherent speed and agility. It became apparent that this would require the utilisation of new technology, particularly in the area of head and eye-slaved visual displays; studies within the MoD confirmed this and concluded that although innovative, the application of such technology was feasible. This paper reviews some of the background and selection process and briefly describes the mission simulators selected to meet the Royal Air Force's training needs.

1. INTRODUCTION

The Harrier GR MK5/7 aircraft have an exacting primary operational role in low level offensive support, operating at speeds in excess of 500 knots at low altitude, over undulating terrain by day and night in all weather conditions. Tasks are performed under manual control using visual references only, without the benefit of terrain following radar. Visual references are enhanced in low light conditions by the use of Forward Looking Infra-Red (FLIR) and Night Vision Goggles (NVG).

Operating the aircraft within the complexities of a modern ground/air warfare scenario with its sophisticated electronic defence mechanisms creates a potentially hazardous environment with a high pilot workload. Thus in 1984 the training requirements for Harrier GR MK5 conversion and ab initio pilots were the subject of extremely careful consideration by the Royal Air Force at Air Staff level. Their deliberations were influenced to some extent by the then prevailing decision by HM Government not to procure dual-seat training aircraft, a situation which increased the emphasis on the requirement for comprehensive synthetic training.

In the event, synthetic training suites comprising Computer Based Trainers (CBT), Procedures Trainers, (Harrier Avionics Systems Trainer (HAST)) and mission simulators were identified and placed on order. This paper deals with the mission simulator aspects of those training suites.

The Air Staff's requirement demanded a mission simulator capable of providing the full spectrum of VSTOL operational flying training together with means of controlling and evaluating aircrew performance within flexible wartime scenarios which were to include Nuclear Biological and Chemical (NBC) and Electronic Warfare (EW) conditions. Further, the ever more vocal environmental lobby with its demands for curtailment of low level day and night flying served to emphasise the desirability of seeking technological solutions to providing operational training synthetically rather than in the actual aircraft.

Fig. 1 Harrier GR Mk 5 Mission Simulator

Research within MoD establishments such as the Institute of Aviation Medicine at the Royal Aerospace Establishment Farnborough and elsewhere, indicated that to provide effective training, in addition to the obvious requirement for high fidelity flight and systems simulation, the mission simulator would require a visual system of exceptional capability in 1984 technology terms. The visual display system would require a Field of View (FOV) capable of providing the full range of retinal (foveal and extra-foveal) visual stimuli deemed essential to elicit correctly correlated pilot reactions. This is particularly relevant when controlling the aircraft at low level, during the inherently unstable conditions possible with VSTOL aircraft during transition, during air to air refuelling operations and air combat, when, in addition to the line of sight visual information important rate cues are received via the pilot's peripheral vision.

The Harrier mission simulator visual system display FOV therefore was required to be as near as practicable to that of the aircraft and the specification set a requirement of +80 degrees in elevation -50 degrees in depression and $\pm$120 degrees in azimuth, from the pilot's eyepoint.

The display system was required to interface with a high resolution Computer Generated Image System (CGI) capable of reproducing high scene detail in tactically significant areas at rates compatible with the operational speed and agility of the aircraft, from data bases compiled from terrain data and enhanced with feature detail from 1:50,000 scale topographical charts. MoD investigations into the technology available to fulfil these requirements indicated that a requirement to continuously display and update a high resolution CGI in real-time over the total 130 x 240 degrees FOV was unlikely to elicit a cost effective technical solution, however a number of potentially viable slaved Area-of-Interest (AOI) displays were in various stages of development by industry in the USA. It was in this area that the MoD concentrated its search for a technical solution to the mission simulator training requirement. It was also apparent that visual cues alone would not provide the required level of simulation, indeed research findings indicated that to be training effective the visual system should be integrated with a simulator, the dynamic elements of which would provide accurately correlated haptic (mechano receptor induced), and vestibular cues to compliment the retinal stimuli. How this has been achieved is described below.

2 THE SELECTION PROCESS

MoD (PE) issued the formal Invitation to Tender in May 1986. A key requirement was that for each visual system offered tender evaluation would include a formal demonstration which directly related to the system being proposed.

A ten man evaluation panel comprising senior representatives from the Operations, Engineering, Training and Scientific elements of the MoD was established to examine technical proposals in detail. Two Harrier front-line pilots were co-opted onto the panel; their job was to "fly" each bidder's demonstration equipment in order to evaluate its merits for the fundamental low flying training task and advise the evaluation panel.

A separate panel evaluated the commercial aspects of the contractor proposals.

The selection process took place between August and December 1986, a period of intense activity for the evaluation team. The United States element of equipment demonstration evaluation began at Washington DC and over a fourteen day period a team visited Binghamton NY, Pittsburgh, San Francisco, Phoenix, Salt Lake City, Orlando and Daytona Beach. This was followed by further demonstrations in the UK; an exhausting but extremely valuable exercise.

In a close-run competition the recommendations of the evaluation panel were endorsed at Minister level and the visual system selected was the Singer-Link (now CAE- Link) MODDIG/ ESPRIT combination. Singer Link-Miles (now Link-Miles Limited part of the Thomson CSF Aerospace group) were selected as prime contractor to design and build the core simulator and integrate the three major elements.

The actual selection methodology and the rationale behind the selection remain confidential to the MoD however, it can be said that Link's ability to formally demonstrate the functionality of the prototype ESPRIT system in its test bed played a significant part in the process.

3 THE TECHNICAL SOLUTION

3.1 Introduction

The specification for the mission simulators called for equipment capable of providing a wide range of synthetic operational flying training. This presented a number of interesting engineering challenges. The configuration of the dynamic element of the Mission Simulator reflects the requirement for a large FOV visual display area, to enable the practice of high speed low level ground support operations.

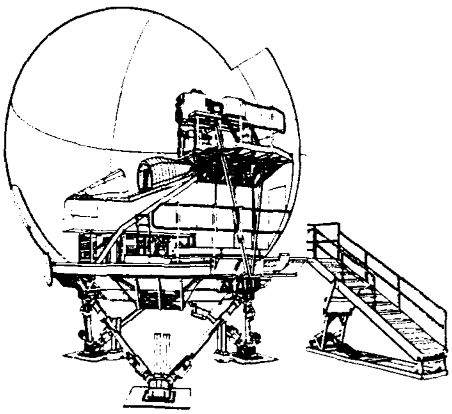

Fig. 2 Harrier Mission Simulator Configuration

The cockpit assembly is mounted on the motion platform forward of the electronics linkage cabinets which are surmounted by a platform bearing the visual display system projectors, optical trains and servos, all totally enveloped by a 24' diameter visual display dome. The entire assembly is mounted on a six degree of freedom, hydraulic motion system. All computers, and the majority of the electronics cabinets and instructor facilities are located off-board.

3.2 Visual System

Visual imagery emitted by two GE light valves is projected onto the high gain (8:1) interior surface of the dome. The dome is a rigid glass fibre composite structure designed to withstand the rigours of motion dynamics and forms part of the CAE-Link Eye Slaved Projected Raster Inset (ESPRIT) display system. The problem of displaying a high resolution CGI over a large FOV is solved by taking advantage of the fact that the human eye can resolve high level detail only within a relatively small area, the peripheral imagery perceived outside this area being of lower resolution. The ESPRIT therefore blends a high resolution area-of-interest (AOI) of 18 degrees within a total field-of-view of lower resolution. The AOI is slaved to the pilot's eye and head movements via a closed loop servo system activated by sensor devices mounted upon and within the pilot's helmet.

The complete system, known as the Helmet Mounted Occulometer System (HMOS), comprises a charge coupled occulometer device, effectively a miniature camera which tracks the pilot's eye movement. Eye position data is correlated with head position data measured by magnetic sensors within the helmet. The HMOS emulates the human saccadic suppression system which closes down optical signals to the brain during eyeball movement, thus the AOI is closed down during transit across the dome surface and regenerated at the new point of focus, so that wherever the pilot looks he perceives only the high resolution image within the AOI. This all happens very quickly and the HMOS system is designed to cope with saccade step responses in excess of 700 degrees per second and accelerations of up to 50,000 degrees per second per second. The HMOS system can also be used when the student pilot is wearing NBC equipment.

The lower resolution peripheral image is displayed via a wide angle lens designed to cover the specified FOV. The high resolution AOI is projected via a small servo-controlled mirror and the system also controls three other servos which maintain AOI size, focus and brightness level as its direction and focal length changes.

Fig. 3 The Helmet-Mounted Occulometer

Another unique aspect of the system is utilisation of the head motion data to shift the visual image in response to head movement to create relative motion and perspective of objects in the scene. This provides useful parallax cues which can add the sensation of a third dimension to the visual scene.

3.3 Image Generation

The visual system imagery is produced by CAE-Link's high performance Modular Digital Image Generator (MODDIG) system which was designed to interface with the ESPRIT display. MODDIG provides two channels of imagery, one for the AOI and the other for the peripheral elements of the scene. A third channel provides the means to simulate the Harrier Angle Rate Bombing System (ARBS) and Forward Looking Infra Red (FLIR).

The MODDIG provides a comprehensive range of specified visual effects including air to ground, air to air, SAM and AAA weapon effects and correctly correlated dynamic ground, air and maritime targets using the techniques of texture, smooth shading and translucency to good effect. Real time mapping functions to pre- distort the imagery to enable its display on the curved surface of the dome and high speed data selection are achieved within the system.

In addition to the specified deliverable land and sea databases, a suite of database generation tools is provided which includes an automatic DLMS terrain data transformation facility and the means to enhance the resulting data base with features and target models. This facility allows the amendment of existing and the production of new databases and models providing potentially world-wide capability.

4 AVIONICS, WEAPONS & FLIGHT SYSTEMS

4.1 Introduction

There is little point in providing the simulator with a technically advanced visual system unless the core simulator flight handling, engine performance, avionics and weapons management systems simulation attain compatible levels of fidelity, observing that the final training system is a totally integrated entity. This being the case a great deal of effort was expended in identifying optimum approaches in all areas, the criterion being (as always) that all systems function and react as those of the real aircraft to maximise training transfer.

4.2 Avionics and Weapons Management

Fidelity of avionics system simulation is optimised by interfacing either actual aircraft or simulated systems with a simulated 1553 Muxbus, controlled, as in the aircraft by a Mission Computer (MC). Unmodified aircraft Operational Flight Programmes (OFP) are loaded into the MC and the simulator system is designed to respond to instructor initiated or programmed freezes and resets. The system is also capable of accepting customer amended OFP's without the need to amend simulator software, enabling aircrew to experience the impact of the OFP amendment on the aircraft systems in the simulator.

The only modified item in the avionics suite is the Head-Up-Display (HUD), although the modification is not readily apparent without close scrutiny of the hardware. The GR Mk5 HUD and GR Mk7 Night Attack HUD optical trains are modified to reduce the focal length of the displayed symbology and FLIR from infinity to a distance coincident with the visual display dome inner surface. The symbology is also remapped to maintain its's correct size and spatial relationship with the hardware. Both the Head-Up and Head-Down Multi Purpose Displays (MPD) are driven by an as-aircraft Display Processor (DP).

The Electronic Warfare (EW) and Weapons Management systems including the Angle Rate Bombing system (ARBS) are also fully simulated. Standby instruments, including an HSI are simulated instruments designed and manufactured by Link-Miles.

4.3 Flight Handling and Performance

During flight the simulator provides a correctly synchronised range of environmental and pilot initiated psycho-physical cues commencing with the on- set movement of the motion system which provides haptic and vestibular stimuli, these cues are perpetuated as required, by the G seat/G suit system and confirmed by the visual system. They are supplemented by digital aural cues and the reactions of displays and instruments which are individually timed to match the aircraft systems. Primary control feel is very accurately simulated and fidelity maintained using digital control loading.

Historically, latency of response to control inputs has been a significant issue, particularly when simulating high speed agile aircraft on motion systems. Fortunately, the situation has progressively improved as technology has provided the means to reduce the time taken to perform the critical flight loop calculations. The simulator specification called for the total response to primary control input to be completed in some 220 ms. In the event response times from control input to visual system update in the order of 130 ms are achieved, much nearer to the aircrafts' inherent latency than has previously been the case.

This is achieved by controlling the three major elements of the simulator i.e. Core Simulator, MODDIG and ESPRIT with

similar micro processor based parallel processor systems interfaced via shared (global) memory, and operating where appropriate at an iteration rate of 60Hz.

4.4 Engine and Miscellaneous Systems

The aircraft engine, its ancillary systems and all electrical, hydraulic and gaseous systems are accurately simulated. In addition to the G seat and G suit facility the pilot may actually initiate ejection if circumstances demand. This will simply bring the motion system to rest and freeze the sortie. However, at the Instructor Operator Station a model based upon actual seat test data will automatically calculate the pilots' chances of successful ejection based on the flight parameters extant at the point of initiation.

G forces are simulated by the G seat and G suit facility. Cockpit lighting and the visual scene also react. As sustained G forces are simulated the visual scene collapses progressively from the outer edges of the peripheral display finally utilising the variable AOI size capability inherent in the HMOS to provide a "tunnel vision" effect adding a further element of realism to air to air combat training.

4.5 Instructor Operator Station (IOS)

Training sorties and pilot activities are planned, controlled and monitored at the Instructor Operator Station (IOS). The IOS provides facilities for a flight simulator instructor and an aircrew instructor but is designed for single instructor operation if required.

Control is exercised from a user friendly push-button control console and all information concerning the simulator and the sortie is presented to the instructor via high resolution colour monitors.

Significant features apparent to the pilot in the visual scene are presented to the instructor via three 24" colour monitors. This facility is effectively a separate graphics generator based visual system the data bases for which are compiled from the same source data and run synchronously with the MODDIG. The scene displayed can be enhanced with additional graphical information such as height posts, target positions, and identification data to optimise the instructor workload. A cursor slaved to the HMOS indicates where the pilot is looking and the pitch and roll functions can be frozen if required, to obviate continuous horizon movement during prolonged periods of agile manoeuvring.

Other monitors provide displays of control function pages from which the instructor can select, enter and vary a range of ambient conditions and introduce aircraft system malfunctions during the sortie to enable practice in reversionary and emergency procedures, and evaluate student reactions. Other displays repeat cockpit head-up and head-down displays and instruments status. All cockpit control panels and Hands on Throttle and Stick (HOTAS) controls and switches are repeated at the display console on mimic panels.

The mimic panels reflect the design of each cockpit panel, are laid-out in as near to the cockpit configuration as possible and indicate changes of cockpit switch/control status as they occur, providing instantaneous information and switch history data to the instructor.

A tactics development facility at the IOS provides the instructor with the means to develop tactical scenarios off-line from a comprehensive and expandable target and ground threat library. The resulting scenarios are fully interactive with the related core simulator aircraft systems, (for example the EW system) and the visual system. During the sortie the instructor can direct and participate in tactical operations, monitoring all interactive own-ship and dynamic target activity via a tactical display at the IOS.

The IOS offers the instructor a wide range of facilities including 30 minutes of record/replay, weapon scoring, freeze/reset facility etc.

4.6 Remote Debrief Facility (RDF)

All major elements of a sortie are recorded on VCR and disc and may be replayed for analysis/debriefing at the RDF. The RDF comprises two independent systems which allow debriefing to take place whilst the next sortie is in progress. All tactics elements are recorded and one monitor of the RDF is dedicated to a repeat of the pilot's visual forward field of view. This facility can be utilised to view own-ship line-of-sight from another spatial view point e.g. from a ground threat point of view as own-ship transits the tactical scenario.

4.7 Night Attack Training

Currently the first mission simulator design reflects that of the Harrier GR MK5 aircraft in that night attack training is limited to the use of NVGs. The second mission simulator design reflects that of the Harrier GR MK7 night attack aircraft. The video output of the MODDIG FLIR channel is modified electronically to introduce characteristics of the aircraft FLIR system.

The resulting imagery is displayed in the Night Attack Head-Up Display (NAHUD) and either of the Head- Down Displays. Other changes to the avionics system such as NVG compatible lighting and the introduction of multi purpose colour displays (MPCD) and Video Map Generation System (VMGS) are also simulated.

NVG training will be conducted in both simulators using special NVG helmets which utilise the HMOS in head-slaved mode with the high resolution AOI expanded to 40 degrees. This provides the same head slaved FOV as perceived by the pilot when using NVG in the aircraft and provides the capability to practice operations using either FLIR or NVG in the safe environment of the simulator and experience the effects of typical system malfunctions before undertaking actual flying operations.

5 CONCLUSION

Within the limits of this paper it is not possible to be other than somewhat superficial in the description of this complex procurement, however, those experienced in defence procurement and tactical training requirements will have recognised that the design and production to the required quality of three technically advanced and substantially innovative elements, each separated by many thousands of miles, culminating in their integration in the UK, presented a significant challenge to both the MoD, the prime contractor and the principal sub-contractors.

The first simulator successfully completed rigorous factory acceptance testing by the MOD in June this year and is currently undergoing recommissioning at RAF Wittering in anticipation of becoming ready for training in December.

It is significant that the principles of those areas of technology which originally represented the highest technical risks have been proven. These include the operation of a display dome on a motion system, the use of eye slaving with aircrew spectacles and the provision of a production capability for large areas of visual system data base with the degree of scene content required for low level operations.

As is to be expected on a project of this complexity the final proof of training effectiveness will only emerge when the simulator is in service and a few practical milestones remain to be achieved, such as the regular use of the HMOS with the NBC Mask during operational sorties and the optimisation of NVG and FLIR simulation on the second (GRMK7) simulator. These are also scheduled to be achieved this year, the latter in conjunction with the MOD'S night attack systems specialists.

In order to make best use of the technology applied to the Harrier mission simulators in terms of piloted simulator effectiveness, two Harrier GR5 current squadron pilots were appointed to test the simulators throughout the engineering test and acceptance phases and advise the contractor on fidelity. Implementation of this important policy has allowed a significant amount of comparative testing to take place and perhaps even more significantly has provided good initial indications that all the necessary cues are available to enable high speed low level training and that the simulators will play their part in the development of piloting skills when in service.

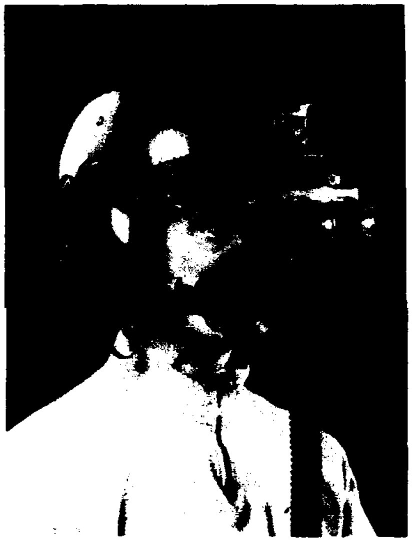

Fig. 4 Harrier NVG Helmet Assembly

6 ACKNOWLEDGEMENTS

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DEVELOPMENT AND EVALUATION OF AN "ATTACK AND MANEUVERING SYSTEM" WITH COMBAT DEVELOPMENT SIMULATORS AS MAIN DEVELOPMENT TOOL

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SUMMARY

As a result of conceptual design work on future fighter aircraft and of future Air/Air weapons it was concluded that in future Air/Air combat, especially in the Beyond Visual Range (BVR) scenario, a pilot has to be supported by means of intelligent onboard processing equipment in order to fulfill his most demanding tasks by fully exploiting the weapon system capabilities.

An integrated fire and tactical flight director control system was developed for the entire air combat arena by DASA MBB's Military Aircraft Division in its manned simulator facility. A description of the developed system and the used simulator facility is given.

As a first step to verify this development the Attack and Maneuvering System (AMS) for the BVR - Air Combat was successfully evaluated by the German Luftwaffe in a large scale manned realtime simulation study. It was demonstrated that such a system can significantly improve the combat effectiveness of a modern fighter aircraft in the BVR - scenario by a factor of up to 6 (depending on scenario).

1. INTRODUCTION

During the late seventies and the early eighties Operation Research studies and mannned simulations were conducted by MBB to investigate the impact of future Air/Air weapons on air combat and fighter design ([1] to [6]).

The new feature of those weapons was the all aspect capability of Short Range missiles. This capability was requiring automatically that also the gun had to have an all aspect capability in order to be useful (Fig.1).

Operations Research investigations were showing that air combat starting in the Beyond Visual Range (BVR) was often leading into a Short Range (SR) combat situation. It was not possible to separate the low subsonic and high supersonic combat arena without loosing combat effectiveness. In particular it was found that the introduction of reliable look down/shoot down radars and Medium Range Air/Air Missiles alters the nature of the BVR - Air/Air combat significantly. When employed both on the "blue" and "red" side they force the opponents to maneuver in offensive and defensive manner in a rather high supersonic speed regime over extended periods of time. This necessitates tactics and maneuvers which are difficult to employ and to assess by a pilot due to the highly

dynamic nature of the BVR - combat and therefore little time is left for gaining Situational Awareness (SA).

The time critical decision making process for threat assessment, target recognition and designation, prelaunch maneuvering, weapon employment and escape maneuvering calls for an initial movement as early as possible for the fighters success and survival. External and internal sensor informations must be acquired, processed and used immediately to keep pace with the rapidly evolving scenario.

A pilot left with the manual tasks of simultaneously flying the aircraft, operating the sensors, comprehending the tactical informations from displays and coming to tactical decisions would be severly overtaxed in its ability to cope with the speed of rolling events in such an airbattle.

Consequently the need for computerized sensor operations and fusion, tactical decision assistance and automated optimum flight path advice was recognized.

2. ATTACK AND MANEUVER SYSTEM (AMS) CONCEPT

In todays fighter aircraft sensors are operated manually by the crew. Acquired data are presented to the crew which must correlate the data from different displays and derive the tactical situation to come to the appropriate tactical decisions. An automated system must perform in a similar manner to be accepted by pilots.

These functions (Fig. 2) are:

- Sensor Management
- Sensor Fusion
- Tactical Processor and Fire Control
- Pilot Vehicle Interface
- Resource Management

All the relevant/necessary informations about performance and state of opponents, weapons, own aircraft and the intended mission must be made available to the onboard computer in order to derive the situation assessment and the appropriate tactic. These informations yield to a maneuver and weapon employment proposal which are presented to the crew via the PVI. It's now up to the crew's decision whether to follow this proposal or not, leaving the crew in control of the aircraft and in command of the airbattle.

3. SENSOR MANAGEMENT (Fig. 3)

Based on the knowledge of effective sensor ranges, Ground Control Intercept (GCI) station informations, assumed opponent tactic and performance and the situation assessment of the tactical computer the Sensor Management controls the aircraft sensors in terms of their field of view, scan patterns, operating modes and other parameters. It relieves the crew workload from most of the radar and Infrared Search and Track System (IRSTS) operation.

Radar operation is limited as much as possible by crosscueing the radar to Radar Homing And Warning (RHAW) and IRSTS contacts to avoid any unnecessary search operation of the radar.

Crosscueing and target extrapolations are reducing reacquisition times after evasive maneuvers which can create lock breaks due to gimbal limitations of sensors.

Search and reacquisition operations use any previous knowledge and predicted target flight path combined with a coordinated search maneuver in order to minimize

reacquisition times to reach a time and position advantage over the opponent. In critical combat situations several seconds can be gained compared to manual sensor operations in the manned simulation study.

4. SENSOR FUSION

All sensor informations are transformed into a common coordinate system. Sensor contacts are processed into sensor tracks, sensor tracks are fused into corporate tracks which contain all target relevant informations.

These tracks comprise position, velocity, maneuver load factors,radar and IR emissions and an assessment of possible target behaviour (agressive/ non agressive).

Based on observed opponent tactics and assumed intentions tracks are long term extrapolated if a lock break occurs. This helps to maintain the Situational Awareness (SA) and accelerates the reacquisition as soon as targets might reappear in the defined field of view.

5. TACTICAL PROCESSOR AND FIRE CONTROL

The Tactical Processor (Fig. 4) is the heart of the AMS. Using all available informations from the corporate tracks, threat assessment, possible own and opponent maneuver and weapon potentials an Onboard Simulation (OS) is performed in the BVR-combat to derive the outcome of possible opponents firings under various own maneuver assumptions (it is hereby not assumed that a sensor exists that can detect an opponent's firing).

Based on these OS results a Safe Time is calculated which is the time available to continue the present attack before a defensive maneuver must be executed in order to avoid an assumed counterfire to become effective. Simultaneously an own Time To Fire (TTF) is calculated for effective Medium Range Missile (MRM) firing(s) and displayed.

An Inrange Computation takes into account a set of possible target maneuvers and yields missile ranges under these assumptions.Both own and the opponent ranges are calculated. However, these missile envelopes are only presented on the displays. They are not used for fire control purposes.

The OS adapts in real time to the evolving situation and allows a continous prediction of probable events. Based on this prediction advices are continously calculated and presented how to maneuver the aircraft and when to employ the weapons to achieve the best possible results. After weapon release the system calculates the necessary missile update and illumination times before they can fly autonomous and assesses their potential of hitting the target.

Short Range maneuver advices for missile deployment are based on "pure pusuit", gun attacks are based on "lead pursuit", (a fuselage aiming system coupled with the flight control system enhances gun aiming) and BVR maneuvers are divided in maneuver sections which are

- Prelaunch
- Postlaunch
- evasive maneuvers
- Reattack
- Search
- and Disengage in case of low fuel, no more weapons or severe disadvantage.

All proposed maneuvers are optimized using the available aircraft flight

envelope and limited by aircraft safety parameters as useful angle of attack, dynamic pressure limit, g - load as well as terrain avoidance and allowable pilot g - strains.

All known opponents are continously tracked, if possible, and their threat potential monitored throughout an engagement in order to maintain SA while fighting the highest threat(s).

The Tactical Processor is implemented as a feedback system which continously accounts for the evolving situation and can adapt to a wide range of tactical events in real time.

6. PILOT VEHICLE INTERFACE

The calculations of the Tactic Processor and the results of the situation assessment are presented to the crew via the Pilot Vehicle Interface (PVI) to maintain the SA and to allow the decision of either following the calculated advices or not. It's also possible for the crew to interfere with the system by changing target priorities, target designation for missile firings and to adjust for own tactical decisions via a specified HOTAS (Hands On Throttle And Stick).

The tactical situation is presented mainly on Head Down Displays (HDD's). Flight and Flight Director (FD) informations as well as weapon employment advices are presented via both the Head Up Display (HUD) and Head Down Displays. Fig. 5 and 6 show a BVR-combat situation as presented in the Tactical HDD and the HUD. Display formats and range selections are automated and constantly adjusted to the present situation needs.

7. RESOURCE MANAGEMENT

Remaining armament, fuel status and other expendables are continously monitored and displayed to the crew if necessary, e.g. a fuel low situation.

8. DEVELOPMENT ENVIROMENT

The AMS has been developed over a period of eight years. Extensive research into available game theory and optimum control algorithms gave limited results only. Eventually a feedback algorithm with a strong heuristic background was developed as a maneuver generator which proved to be equally adaptable to generate short range as well as medium range maneuver advices. This was combined with Sensor Management and Sensor Fusion functions feeding informations into a Tactical Processor.

The Sensor Management system was implemented as a rule based system being a successful application of artificial intelligence techniques in a real time system.

The Tactical Processor supervises the whole system, derives the situation assessment and feeds the maneuver generator as an integral part.

All AMS-functions had to run in real time. They were in fact designed from the start to do so with an affordable amount of computing capacity.

To develop and test such a system a simulator was the only feasible tool. An extensive real time simulation of an air combat scenario has been built, comprising up to four airplanes with sensors, weapons and associated tactics and the manned development simulator with the man-maschine interface.

An overview of the components of the MBB development simulator is shown on Fig. 7. It consists of

- a General Electric Compuscene IV Computer Generated Image System (six channels giving a field of view of 140 x 114 degrees)

- a 30 ft dome

- generic fighter cockpits and helicopter cockpits with buffet-system, g-system and a soon to be installed noise generator

- the Control Console

- the Central Interface

- the real time simulation computer (formerly a HEP with two Programm Execution Modules, since early 1990 a Harris computer with 8 CPU's)

- a computer for programme development (formerly a VAX 780 , since 1990 a Harris computer with 2 CPU's)

- a link to the IABG Dual Flight Simulator.

The simulator proved sufficient for the task, only hampered in Short Range combat due to its limited field of view. Fig. 8 presents a view into the dome with the generic fighter cockpit.

The primary programming language was FORTRAN 77. Sensor Management and Sensor Fusion was rewritten in ADA in 1990 and tested in the real time simulation. The final programme consisted of 96 parallel processes, with a maximum of 44 processes running at the same time.

9. SYSTEM EVALUATION

The AMS was initially developed in a real time man vs. computer enviroment and could only be tested against the limited tactical repertoire of computer generated opponents. There was the question whether a pilot could outmaneuver the computer assisted system.

The IABG Dual Flight Simulator (DFS) provided a good opportunity to verify the computer assisted system against a crew's wits and to prove the soundness of the design. The two manned simulators (Fig. 9) at MBB and IABG where tied up to allow the assessment of a computer assisted piloted airplane against a conventionally piloted airplane.

A large scale manned real time simulation was initiated. The "blue" side was implemented in the MBB's dome simulation facility and connected via a high speed optical data link, over a distance of 2000 meter, with the IABG's two dome simulation facility where the "red" side was implemented. It was decided to verify, as a first step, the AMS in the BVR-Air Combat. Both sides were using identical fighter aircraft, radars and BVR - weapons.

Two different setups were used (Fig. 10), a fighter vs. fighter and a fighter vs. escort fighter plus fighter bombers enviroment (the fighter bombers were computer generated and computer controlled models by IABG). The escort was equipped with a partly enhanced (F-18 type) fire control and situation display system. The blue fighter was equipped with the AMS. For each setup a reference case was performed to measure the increase in exchange ratio when using the AMS. These reference cases were performed in the IABG DFS, where two identical aircraft with the above mentioned F-18 type avionic were flying the air fights (this makes four cases - two without AMS on the "blue" side and two with AMS on the "blue" side).

Over 400 engagements were flown in order to establish a valid basis for reliable statistical results.The flights were conducted by combat ready German Luftwaffe pilots. The campaign lasted about three weeks and included extensive system familiarisation where the crews were evenly rotated between blue and red facilities.

During the training phase and even more during the evaluation phase the pilots could build up a detailed knowledge of AMS capabilities. This led to the adaption of "blue" tactics into "red" behaviour for the study and precluded therefore even better study results.

Fig. 11 shows aircraft and missile trajectories of a BVR - engagement flown during the study. The duration of such engagements is limited to only a few minutes due to afterburner fuel consumption.

The study results [7] were very encouraging in several respects:

- The exchange ratio in the fighter vs. fighter enviroment improved by a factor of about three using the AMS,
- The exchange ratio in the fighter vs. escort fighter plus fighter bombers enviroment improved by a factor of almost six.

It's worth to be noted that the engagements were usually started with a disadvantage for the "blue" fighter.

Fig. 12 shows the absolute fighter losses. These losses include missile kills, RTB- and pressure limit kills. A RTB- (Return To Base) kill was called whenever remaining fuel dropped below a previously defined limit before the aircraft was reaching a specified heading within certain limits (+/- 30 degrees). A pressure limit kill was called when the aircraft was exceeding its dynamic pressure limit.

The result of case 1 clearly reflects the disadvantage of "blue" caused by the starting conditions. With AMS on the "blue" side (case 2) the losses are considerably reduced and the overall exchange ratio reached a value of about one to three in favour of "blue". The same is true when comparing case 3 and case 4 for fighter losses only. Even better results can be seen on Fig. 13 .The overall exchange ratio including bomber losses amounts to as much as almost one to six in favour of "blue".

- Crews expressed great appreciations and acceptance for the overall AMS. Mainly the reduced crew workload and the greatly improved SA provided by the AMS were the key factors.
- Lower average and peak g-levels could be observed on "blue's" side throughout the fights.

The high g-levels which were flown by the pilots without AMS should be looked upon closely. Despite the simulation of g's by blowing up the anti-g-suit and the simulation of "grey out/black out" by reducing or completely shutting off displays and visual system, there is obviously a "simulator effect". A pilot would probably not be able to tolerate these frequently occuring high g-levels of up to 8.5 g.

- Attempts to "cheat" the AMS have been unsuccessful resulting in a solid confidence into AMS proposed maneuvers and tactics on the blue side hence red crews were trying to copy manually the blue tactics.

The PVI was found satisfactory for this simulation campaign however this has to be greatly improved for use in operational aircraft.

The development and testing was stopped in 1989 to due other company priorities.

10. CONCLUSION

It was demonstrated that the capabilities of a modern weapon system can only be fully exploited by the implementation of an AMS - like system and it is achievable with todays technologies.

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[6] Herbst W.B. , "Future Fighter Maneuverability for Air Combat" AIAA Aircraft Design Systems & Operations Meeting Fort Worth, Texas, Oct. 1983

[7] "Operationeller Nutzen des AMS" B/WT 8008/01, Aug. 9, 1989

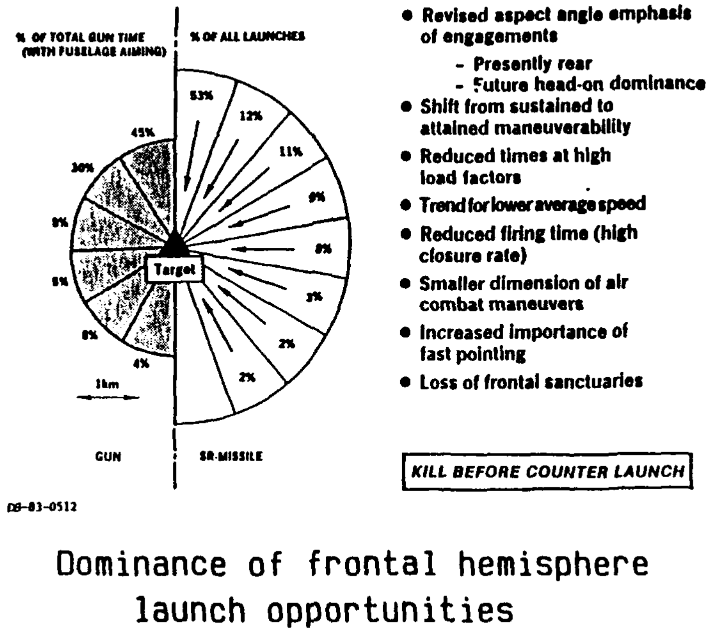

Figure 1

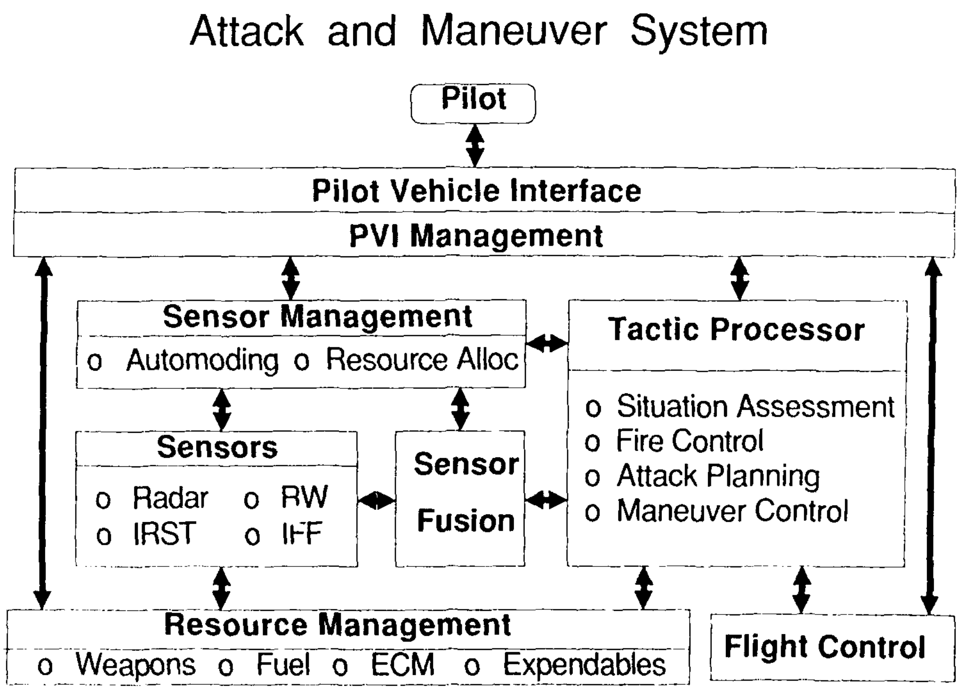

Figure 2

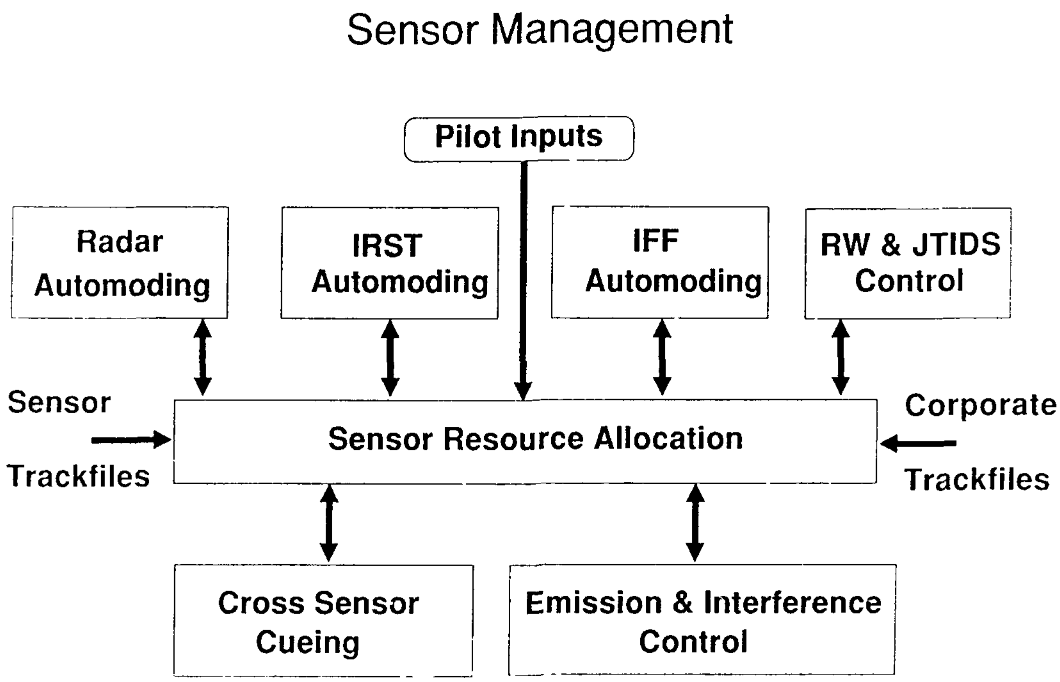

Figure 3

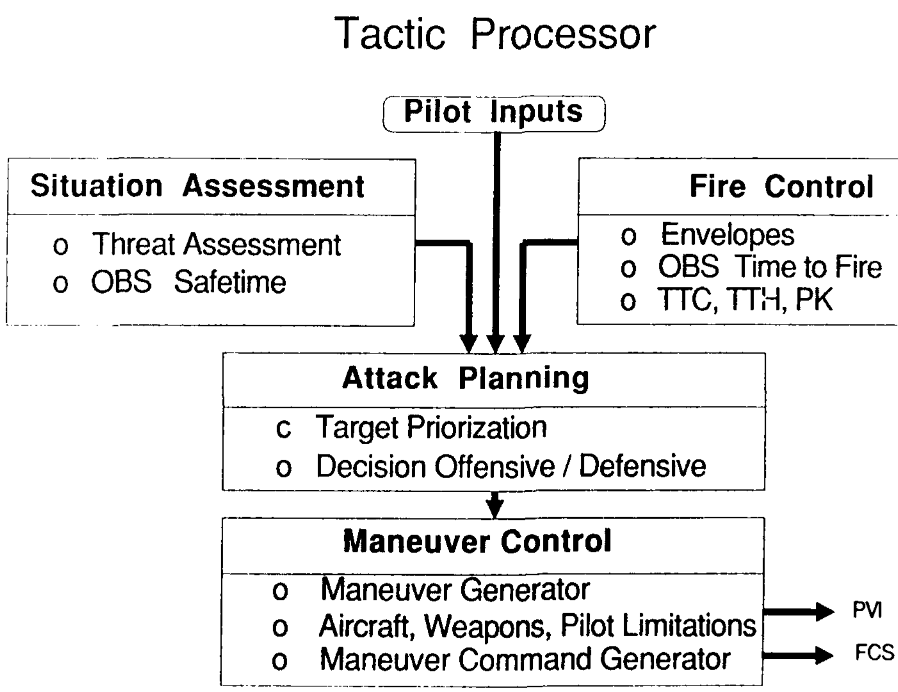

Figure 4

directly related to the system being proposed.

HUD Display Format

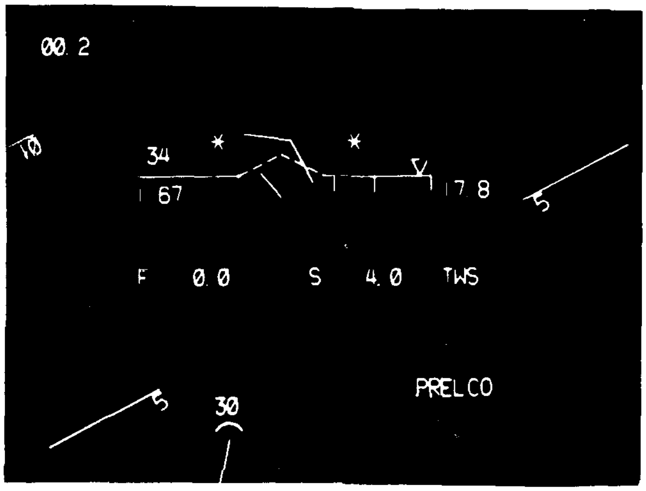

Figure 5

HDD Tactical Display

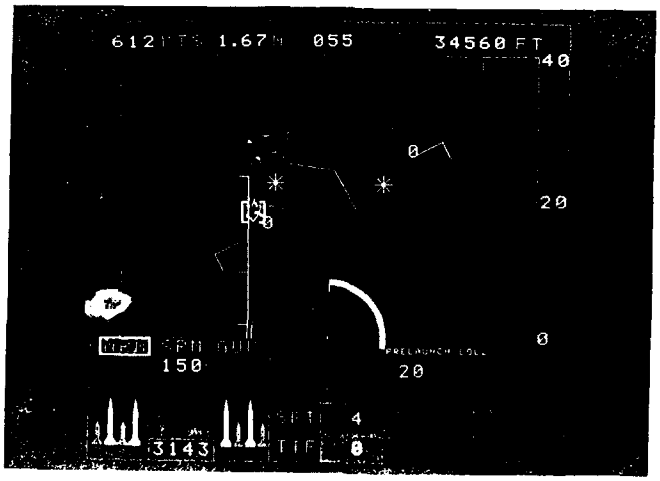

Figure 6

MBB-UL Development Simulator for Aircraft and Helicopters

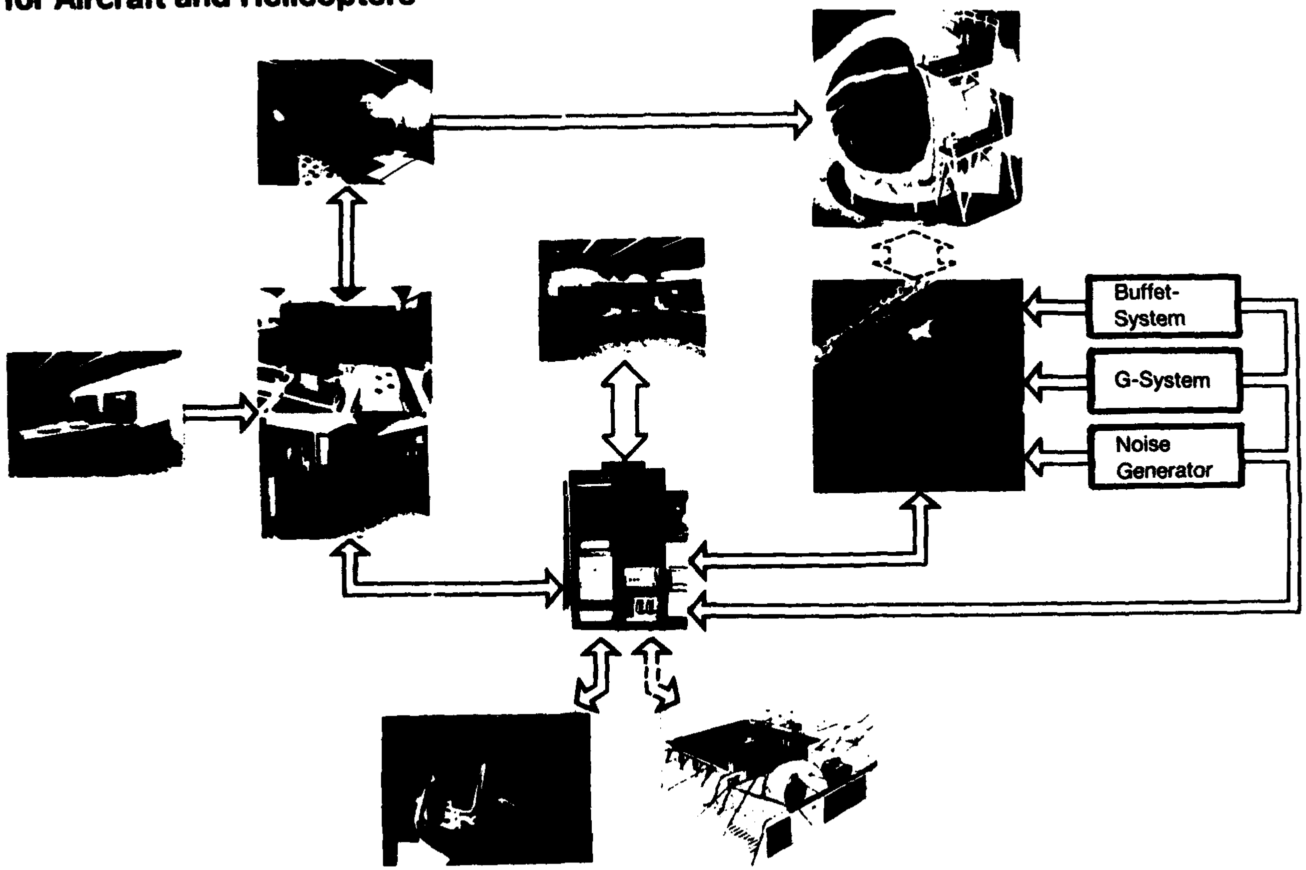

Figure 7

View into MBB Dome

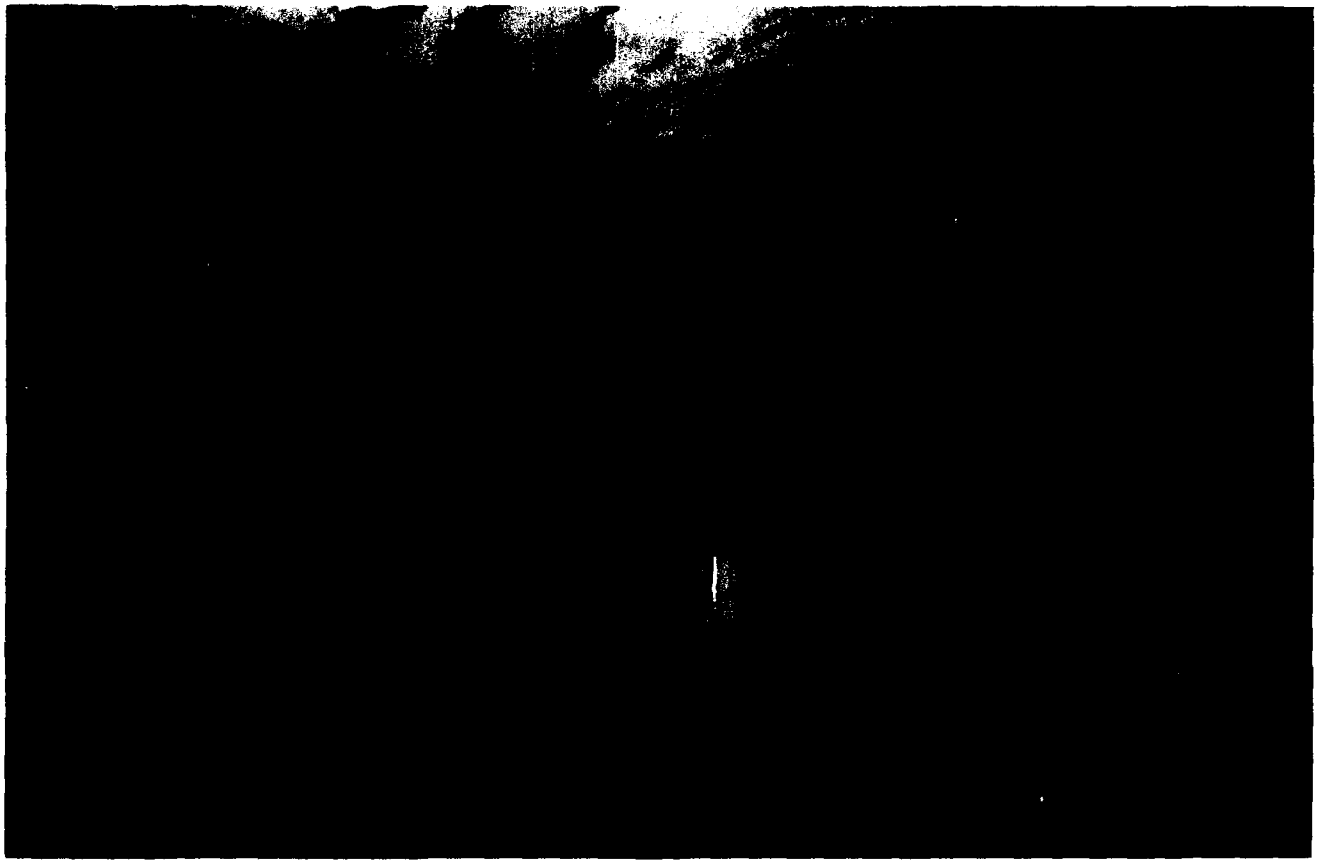

Figure 8

Simulation Setup

Two Manned Simulators plus computed bombers

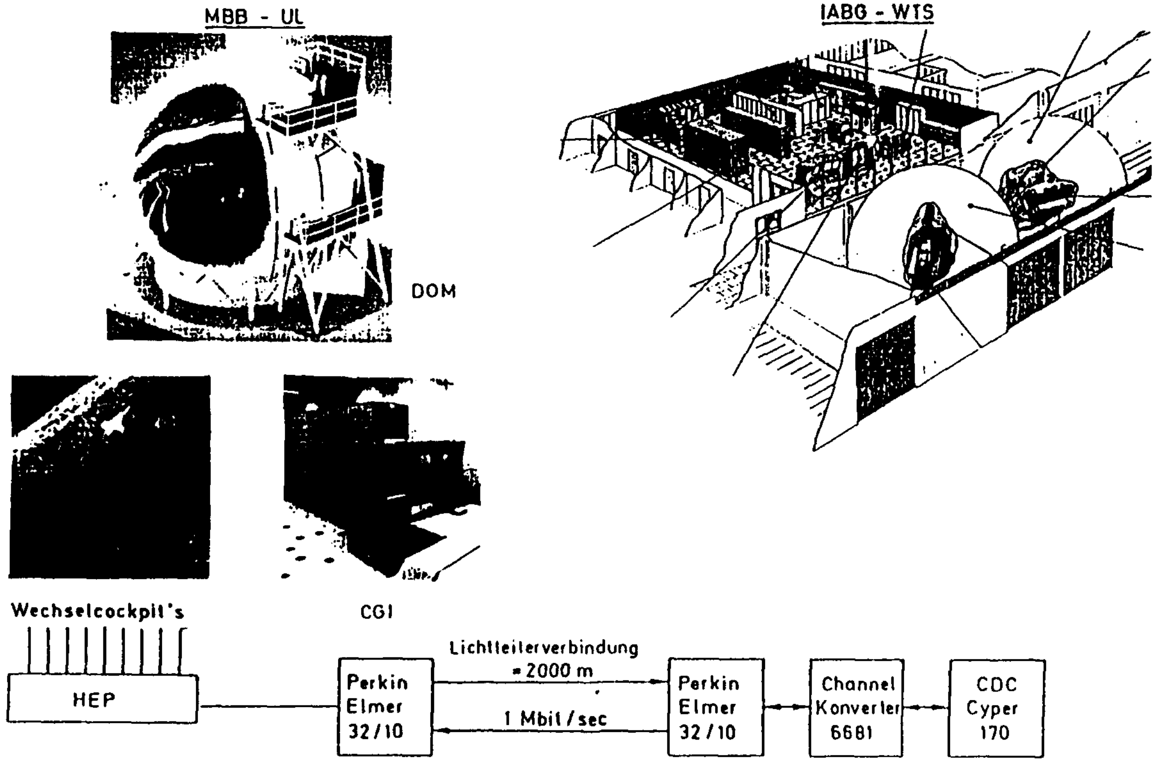

Figure 9

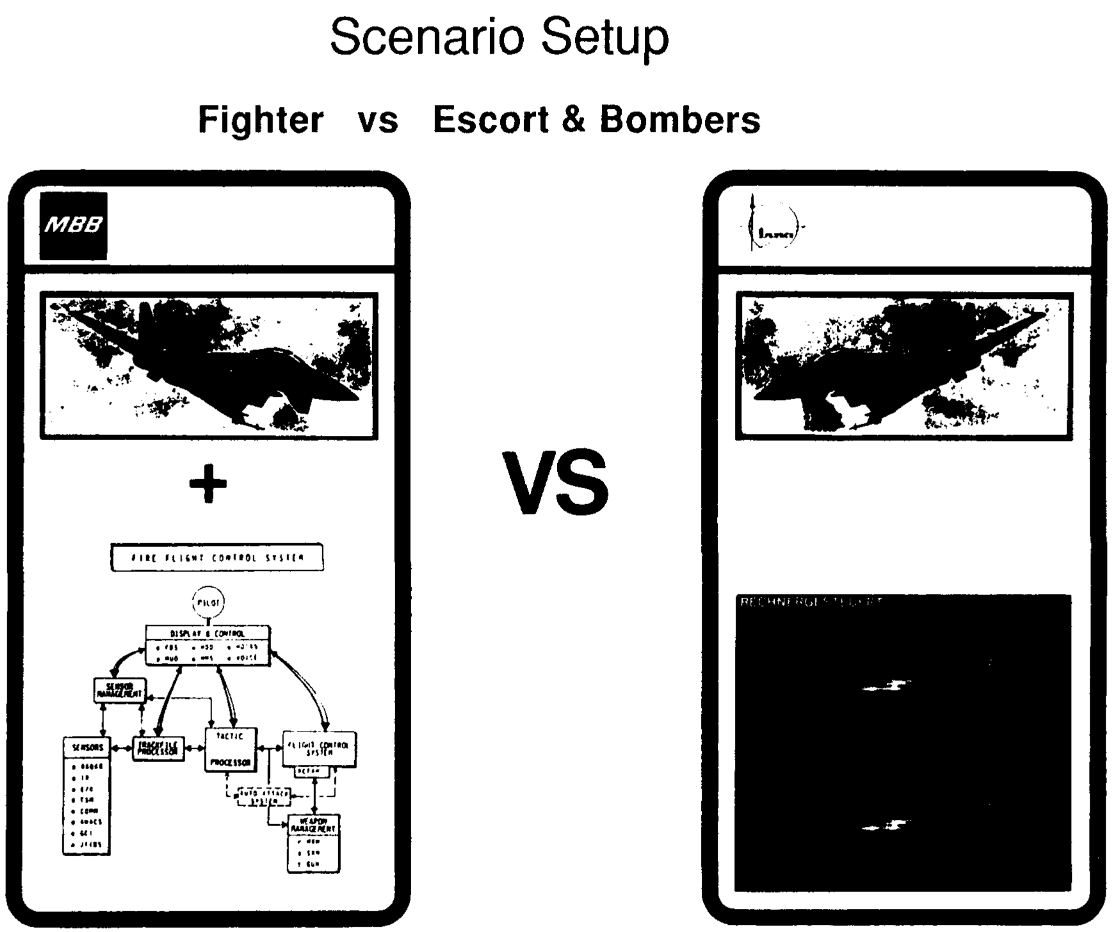
Scenario Setup
Fighter vs Escort & Bombers
MBB
+
FIRE FLIGHT CONTROL SYSTEM
PILOT
DISPLAY & CONTROL
SENSORS
TACTIC
PROCESSOR
FLIGHT CONTROL SYSTEM
WEAPON MANAGEMENT
VS

Figure 10

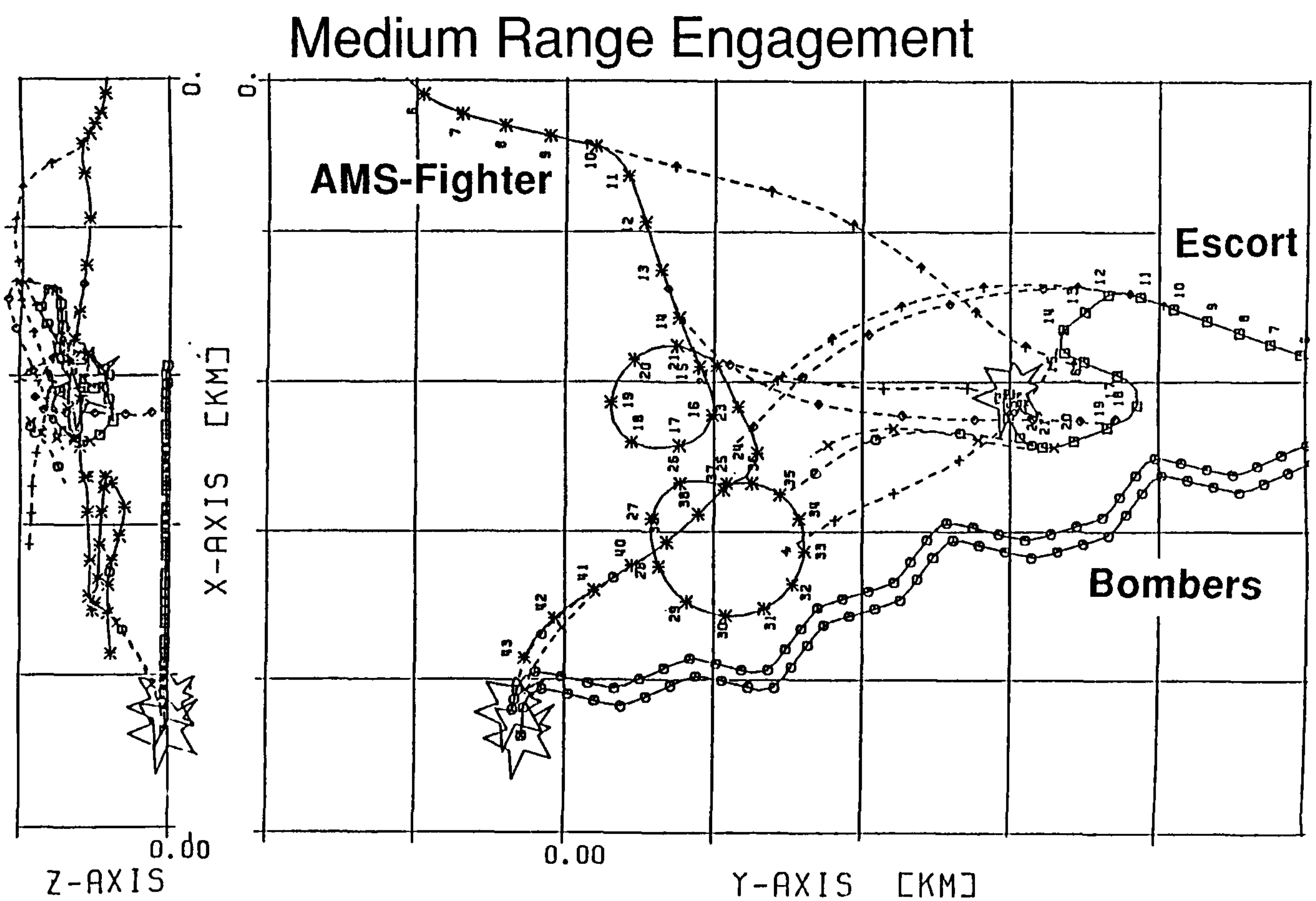
Medium Range Engagement
AMS-Fighter
Escort
Bombers
X-AXIS [KM]
Y-AXIS [KM]
Z-AXIS
0.00
0.00
0.00

Figure 11

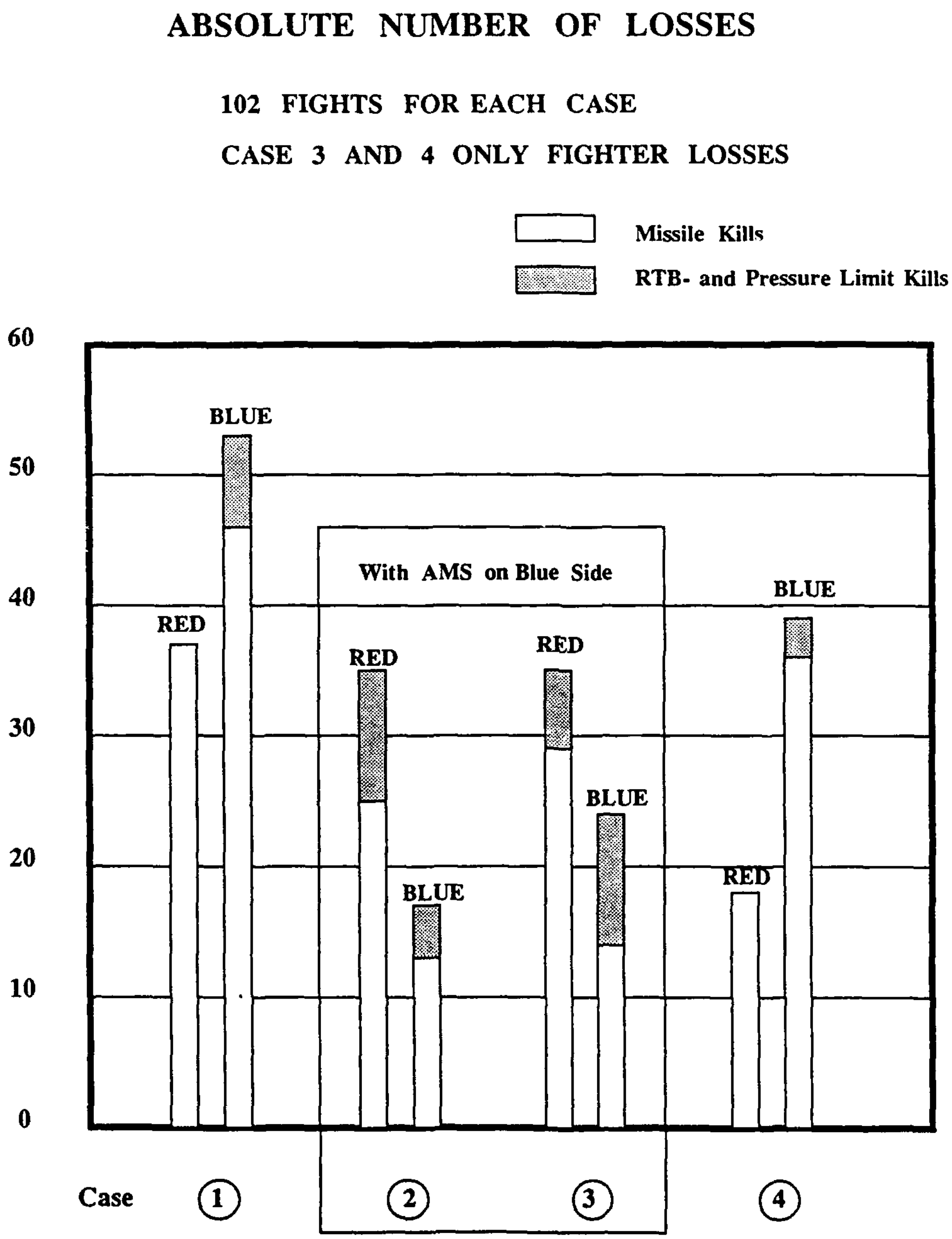
ABSOLUTE NUMBER OF LOSSES
102 FIGHTS FOR EACH CASE
CASE 3 AND 4 ONLY FIGHTER LOSSES
Missile Kills
RTB- and Pressure Limit Kills
60
50
40
30
20
10
0
RED
BLUE
With AMS on Blue Side
RED
BLUE
RED
BLUE
RED
BLUE
Case
1
2
3
4

Figure 12

ABSOLUTE NUMBER OF LOSSES

102 FIGHTS FOR EACH CASE

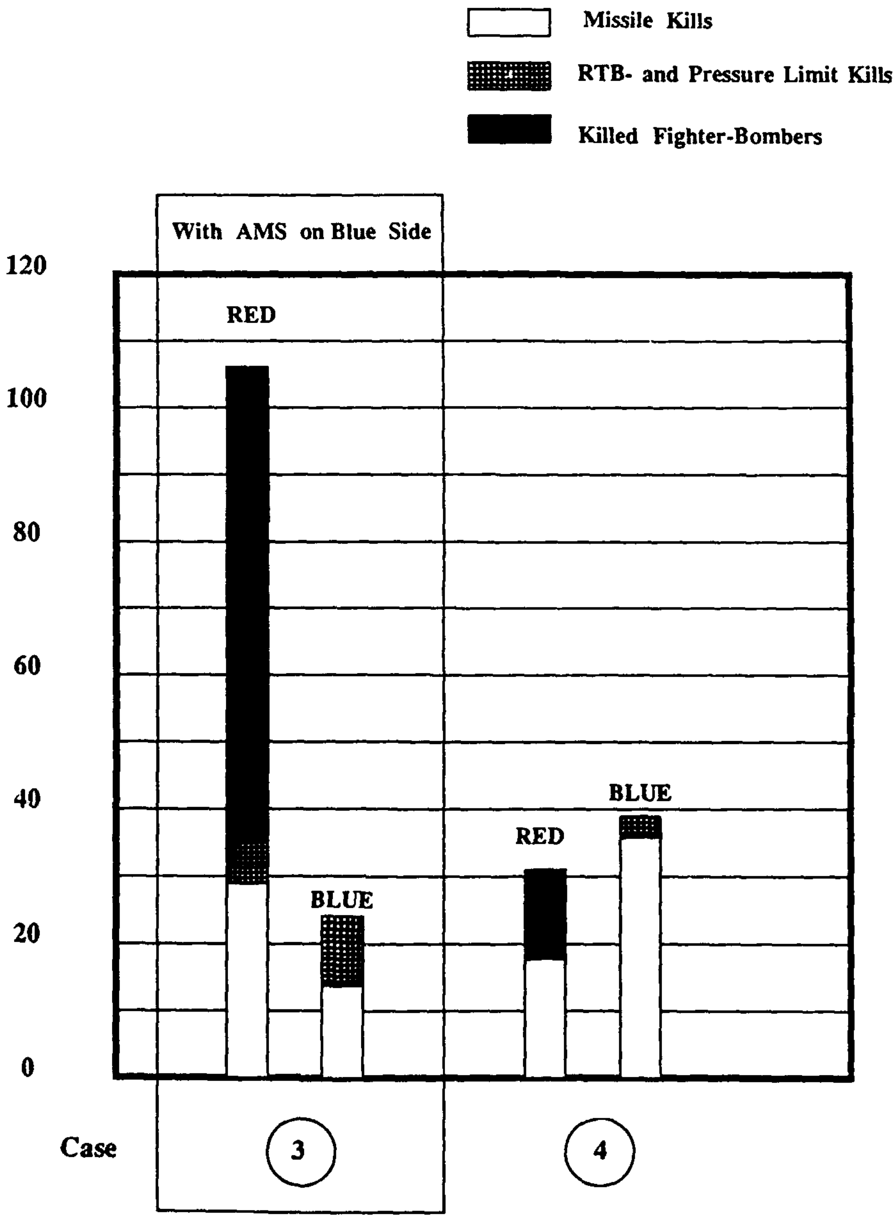

Figure 13

Shipboard Mission Training Effectivness of the Naval Air Test Center's V-22 Government Test Pilot Trainer

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SUMMARY

Initial shipboard compatiblitiy tests of the V-22 Osprey VSTOL tiltrotor aircraft were conducted aboard the USS Wasp (LHD-1) on 4-8 December 1990. Pilot training and engineering analysis for the first shipboard launches and recoveries of the V-22 Osprey aircraft were conducted in the V-22 simulator at the Naval Air Test Center. During these sessions workload data was recorded and the pilots made comments regarding the quality of the training. Quantitative comparisons of time history data have been made using power spectral densities, averages and maximum attained values. Qualitative comments have been compared to the remarks made after the actual at-sea tests. Conclusions are drawn concerning the effectiveness of the training; and suggestions for future improvements have been made.

LIST OF SYMBOLS

IGE	In ground effect
OGE	Out of ground effect
WL	Workload, inch-pounds
PSD	Power spectral density
Hz	Frequency, Hertz

1.0 BACKGROUND

1.1 Helicopter launch and recovery aboard ship are acts which imposes great demands on both the aviator and the aircraft. They are tasks in which success depends on factors that are inherent to both the aircraft and the ship. The helicopter is particularly unfortunate, as it is a fundamentally unstable machine that is required to operate under the most adverse of shipboard conditions to complete its missions. The hazards associatedwith shipboard operations have forced the helicopter test and evaluation community to regard these operations with great respect. While we have liberally used the term 'helicopter' up to now, we would like to emphasize that the tiltrotor has unique capabilties unto itself. For the purpose of simplification, we will use the terms 'helicopter' and 'tiltrotor' interchangeably throughout this paper.

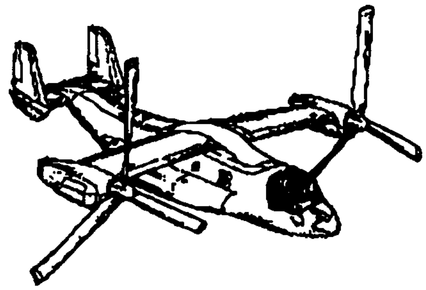
1.2 In the past the U.S. Navy's testing of helicopter shipboard operations came long after most of the Navy's helicopters were acquired. Through years of trial and error, helicopter aircrews have learned shipboard lessons the hard way. However, with the advent of the U.S. Navy's potential acquisition of the V-22 Osprey aircraft, the Full Scale Development (FSD) program required its aircraft prototypes to have the capability to test for shipboard compatibility prior to production. It should be noted that this was the first FSD aircraft program to undertake a shipboard test so early in the development cycle. The shipboard testing carried out was only the second government test series of the aircraft.

1.3 The ability to conduct a shipboard test early in an aircraft development cycle means that the hazards of the test are more severe, as the aircraft itself is still undergoing a development process. This is where the powerful tool of simulation becomes irreplaceable, but only if the simulator accurately replicates both the aircraft and the environment under which the mission is to be performed.

1.4 The United States Navy has constructed and fielded the V-22 Government Test Pilot Trainer which is a full motion, high fidelity training and flight test support simulation. This simulator is the primary training device for the developmental and operational test training for government V-22 pilots. This training system has been upgraded to support the training of V-22 crews in the required procedures for shipboard launch and recovery operations.

1.5 The effectiveness and quality of the training received from simulator flights can be evaluated by comparing quantitative and qualitative data of similar parameters from similar tasks flown during simulator training flights and the actual at-sea flight tests.

2.0 DESCRIPTION OF AIRCRAFT



V-22 Aircraft in Airplane Mode

Figure 1

2.1 The V-22 Osprey (Figure 1) is a tilt-rotor, V/STOL multi-mission aircraft manufactured by Bell Helicopter Textron Incorporated and Boeing Helicopters. Each of the two 6,150 shaft horse power Allison (YT406-AD-400) turboshaft engines are housed in a wingtip nacelle and drives a 38-ft diameter three bladed proprotor. The aircraft is a high wing design with retractable, tricycle type landing gear. The airframe is constructed primarily of graphite-reinforced epoxy composite material. The two proprotor gearboxes are interconnected through a series of drive shafts and gearboxes to maintain rotor synchronization and one engine inoperative power to both proprotors. The tiltrotor design allows the nacelles to rotate through a 97.5 deg arc, from horizontal (0 deg) in the fixed wing mode of operation to aft of the vertical (90 deg) in the helicopter mode of operation.

2.2 The design includes a triple redundant, fly-by-wire digital Primary Flight Control System (PFCS) and an Automatic Flight Control System (AFCS) to control the aircraft. The Flight Control System (FCS) software version used throughout this test was 5.3.2 (patch 064). This version encompasses the PFCS and core AFCS. With the nacelles at or near 90 deg (helicopter mode), the FCS controls the aircraft in a method similar to a twin rotor helicopter. During conversion of the nacelles to 0 deg (airplane mode), the FCS phases out the cyclic rotor swashplate commands and controls the aircraft through the use of conventional aerodynamic surfaces.

2.3 The test aircraft, BuNo's 163913 and 163914, were prototype aircraft which contained on-board flight test instrumentation. This instrumentation provided data from the test aircraft to both contractor and government personnel aboard the test ship. Additionally, aircraft 163913 was configured without infrared suppressors; in their place were installed prototype engine exhaust ejectors and 60 deg deflectors. These components were designed to deflect exhaust gases away from the aircraft and equipment aboard ship.

3.0 DESCRIPTION OF SIMULATOR

3.1 The U.S. Navy's V-22 Osprey simulation in use is located in the NATC Manned Flight Simulator (MFS) facility. The computer models are hosted on the Tactical Avionics Simulation Test and Evaluation Facility computer system cluster. This system is a multi-configuration collection of Digital Equipment's VAX series of machines in association with aircraft mission and flight control computers, visual system generation devices, and the required bus and network interfaces.

3.2 The aerodynamic models are run on an Avalon Inc. processor which is hosted on a Digital MicroVax II. Another MicroVax II is used for the avionics system modeling. These models communicate with a V-22 configured AYK series mission computer via a 1553 bus patch panel. The mission computer in turn communicates to the aircraft quality display processors via 1553 bus interfaces in the simulator. The avionics, airframe and other processes share a common memory which resides in the in-house designed and constructed multiport memory.

3.3 The visual system used is a General Electric Compuscene IV, and the images produced by this system are projected on a Rediffusion Wide II visual display device. This display system is mounted to a Rediffusion six degree of freedom motion platform, which has been modified to accept multiple cockpits in keeping with the MFS modular design. This combination motion base

and visual projection system make up the motion simulation station.

3.4 The eight channels of digitized aural cueing are provided by a pair of Amiga computers. The sound samples themselves have been gathered from both the V-22 and the XV-15 tiltrotor aircraft.

3.5 The cockpit itself was constructed by Seven Bar Systems Inc. to replicate the aircrew work stations of aircraft number BuNo 163912. It is a wheel mounted, moveable device that can function in any of the four simulation stations. For the training described in this paper the cockpit was utilized in the motion station described above. The cockpit is outfitted with actual aircraft Multi-Function Displays (MFDs), display processors, keypads and video display units, and high fidelity simulated instruments.

3.6 The ship models and the ship environment models have all been programmed in-house. State-of-the-art modeling techniques have been employed to replicate four different classes of U.S. Naval ships, and analytical updates are constantly investigated and tested to modify the characterisitics of the ship environment.

4.0 SCOPE

4.1 Shipboard flight testing of the V-22 Osprey was conducted on 7 December 1990 and comprised 12 flight hours at-sea. The three goverment test pilots logged over 40 hours of simulator flight time in preparation starting in late September of 1990. Engineering development and evaluations of the shipboard simulation began in June of 1990 and comprised over 165 hours of simulator flight time. Although simulation training and engineering analysis was conducted for the entire shipboard operations flight pattern, this paper will focus primarily on the most critical tasks: final approach, hover, and landing.

5.0 MEASURES OF EFFECTIVENESS

5.1 Prior to the shipboard training, the V-22 simulator had undergone many tests of its ability to model the actual aircraft accurately in all flight regimes. The unique position of the Naval Air Test Center and the V-22 simulator in the development cycle of the aircraft has created a process that keeps the quality of the simulation at a high state of flight dynamic accuracy at all times. This process is as follows: First, the simulator is used to assist flight test planning of an upcoming portion of the project test plan to insure good use of all available flight time by optimizing the flight test profile, and also to ensure safety of flight. Then, once the simulator has been checked out for training readiness by a member of the test team, the flight test cards are pre-flown in as realistic a manner as possible, with as many of the actual flight test participants performing the same duties they would during the actual flight, whether it be manning strip-charts, monitoring safety of flight data, or performing communications duties. Part of the process is the establishment of all the parameters required for proper flight test data reduction, so a data base can be constructed of expected results by the time flight test occurs

5.2 After flight tests have been completed, the actual results can be directly compared to the predicted, and any required upgrades or corrections to the simulation are performed. Through this constant process of blending results back into predictions, the V-22 simulation has achieved an outstanding acceptance rate with the test pilots who fly both the aircraft and the simulation. The mission tasks have, qualitatively, been a comfortable and believable representation of the tasks the pilots perform in the aircraft. It was with this attitude that the aircrew entered training for the shipboard operations.

5.3 The most visable method of assessing effectiveness of simulator flying qualities and performance, and mechanical characteristics, is to quantitatively compare time history data of simulated flying with actual flight. Of course, if a certain aircraft configuration is planned to be tested with simulation prior to its incorporation into the actual aircraft, a 'best guess' must be made based upon prior simulation knowledge and experience. This was the case during the training and flight test preparation for the V-22's first shipboard testing and evaluation.

5.4 The use of a simulator prior to testing also provides a method of developing test methodology and procedures. Therefore, a post-test measure of the effectiveness of the simulator is to examine whether or not the methods and procedures developed during the simulator training sessions survived contact with the real

world, or had to be modified during the actual flight test.

5.5 Prior to flying at sea, engineers incorporated the latest AFCS code, and upgraded the aerodynamics models to match the latest flying qualities and performance data. This provided a good base model to predict the behavior of the aircraft. The development of flight control system software in a state-of-the-art aircraft is an evolutionary process. Through close coordinauon with the contractor, and an in-house V-22 flight control law expert, the government simulation has followed closely on the heels of the actual development of the flight control system.

5.6 The aural cueing environment of the simulator should recreate noise levels and proper sounds, such as rotor sounds and wind noise inside the simulator cabin. Warning tones and associated emergency sounds, such as an engine spooling down, should be representative of the aircraft.

5.7 The seat-of-the-pants 'feel' of the simulator should match that of the aircraft. This nebulous statement is the pilot's way of lumping together all the intangibles of the simulator and comparing them to the aircraft. The layout of the simulated cockpit, the feel of the seats, the control force/feel system, the windscreen glare, the field of view, in-flight body forces, and many other factors all add up to a single result for the aircrew: the simulator 'feels' like the aircraft or it does not. This is one of the hardest areas to define in a simulator, and thus it can be one of hardest goals to accomplish.

5.8 The same feedback of actual data versus predicted results method is used with regards to the shipboard environment. This simulation is more complex, encompassing the ship motion, ship airwake effects and the gear-ship deck interface. In this case, any known truth data is first gathered, then the simulation models are driven to match reality. For the first shipboard trials, limited data was available on ship motion and airwake, and the interaction of the aircraft with the deck was known only by prediction.

5.9 The shipboard environment should replicate that of the real event. The ship should be the same type, color, and size as the actual. The deck markings should be accurate, and the displacements of the ship island in relation to the deck landing spots should be visibly the same to the aircrew. Height and distance cues should be apparent, without need to reference instruments inside the aircraft for additional information Ship bow and stern wakes, and the water surface must also not be forgotten. Most importantly, the textures and hues of the visual scene must effectively match the real world.

5.10 Finally, the pilots must feel they are getting effective training. What they are seeing must match both reality and their expectations sufficiently to inspire confidence in the ability of the simulator to prepare them for the mission.

6.0 COMPARATIVE RESULTS

6.1 One method used for comparing the simulation to the actual event is through the estimation of power spectral densities (PSDs). The PSD is defined as the modulus-squared of Fourier transform, where the Fourier transfrom is given by

$$\mathcal{F}\{x(n)\} = \sum_{n=0}^{N-1} X(n)e^{k}$$

where

$$k = \frac{-i2\pi n}{N}$$

and the modulus-squared is given by

$$R_x(i) = \sum_{n=i}^{N} x(n)x^*(n)$$

where x^* represents the complex conjugate of x, and so

$$PSD = \mathcal{F}(R_x)$$

6.2 In the case of the V-22 aircraft, this method is most useful for the lateral axis, the dominant workload axis for the aircraft. For the final approach (one-quarter mile to deck edge) section of the landing pattern, Figure 2 illustrates lateral stick activity, with simulator data presented as a solid line, and actual data as a dashed line.

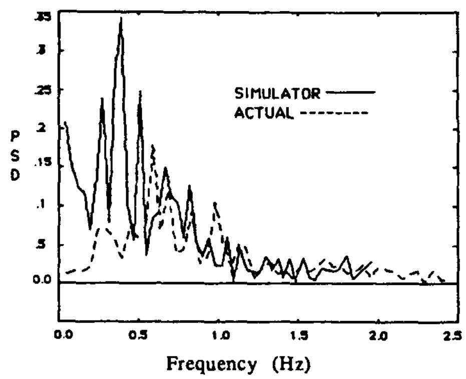


Figure 2
Final Approach

This data shows that during the approach to the deck edge, the actual event required lateral stick inputs of a higher frequency and lower power spectrum as the simulation required to complete the same task. The actual task frequencies were centered around .52 Hz, and the simulation was centered around .48 Hz.

6.3 Figure 3 shows the lateral activity for the deck edge to touchdown task.

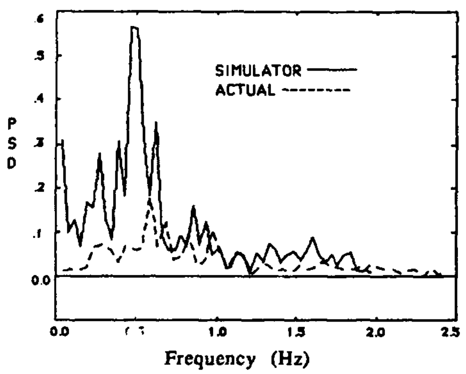


Figure 3
Hover to landing

It can be seen that during the landing phase the simulator required a higher workload than the actual event, and this workload occurred at a lower frequency. The simulator workload was over a wide range of frequencies, centered around .50 Hz, while the actual workload frequency remained in the .52 Hz range.

6.4 An important item to note from the PSD data presented is the percentage increase in workload from the first portion of the landing task to the final section. An increase of 27% is seen in the actual aircraft data, and an increase of 35% is shown in the simulator. So even though the overall workload in the simulator was higher than the aircraft, the increase in workload as the pilot transitioned from the near-ship environment to the landing environment was very similar.

6.5 An analysis of flight control positions, power requirements, time requirements, and basic flight profile characteristics of the aircraft lends insight into how effective the simulation is and how well the update process works. Data are presented in Tables 1, 2, and 3 for three distinct tasks within the shipboard landing pattern; the final approach, the hover, and the landing. Zero percent indicates full left or full aft position, and postive indicates right bank angle.

Table 1
Approach Task

	Simulation	Actual
Rate of Descent (fpm)	250-270	200-225
Task Time Req'd (sec)	20-30	30-50
Lat stick (%max)/average	28-76 /50	48-55 /51
Long Stick (%max)/avg	10-34 /25	56-65 /59
Directional (%max)/avg	25-68 /50	46-49 /48
Mast Torque (%max)	20-83	25-85

Table 2
Hover Task

	Simulation	Actual
Hover Height (feet)	20	20
Task Time Req'd (sec)	8	10
Lat stick (%max)/average	38-57 /52	44-57 /50
Long Stick (%max)/avg	20-30 /25	51-55 /53
Directional (%max)/avg	46-58 /49	47-49 /48
Mast Torque (%max)	69-85	72-85
Bank Angle (deg)/avg	-3 to 4 /0	2 to 3/2.5

Table 3

Landing Task

	Simulation	Actual
Task Time Req'd (sec)	5 - 8	12 - 20
Lat stick (%max)/average	38-63 /52	39-59 /50
Long Stick (%max)/avg	20-30/ 25	50-56/ 53
Directional (%max)/avg	50-68 /56	48-52 /49
Mast Torque (%max)	85-74	85 - 76
Bank Angle (deg)/avg	-4to3 /-1	3 to 5/4

6.6 Controllability of the aircraft during approach is best evident by analysis of glide slope and closure rate with the ship. Initiation of final approach at similar airspeed, altitude and distance entry revealed excellent agreement between the actual task and the simulator. As expected, rate of descent was a bit shallower and closure rate slightly slower during the real-life event because of pilot anticipated consequences of possible error.

6.7 For each task, with regard to control position and range, we see very close agreement in lateral stick, directional, and power requirements between the simulator and the actual event. Only in the longitudinal axis do we see significant differences. Here the range of deflection is very similar, but the average position is approximately 25% different. This has been identified as a weight and balance modeling problem with the simulator.

6.8 The difference of 7 to 12 seconds in time required to land, with the longer duration during the actual landing, is attributed to the fact that actual tests revealed In Ground Effect (IGE) and Out of Ground Effect (OGE) phenomemon that required the pilot to stabilize at a lower hover prior to touchdown. The last anomaly seen is in comparison of aircraft bank angles while in hover and landing. During simulation flight, we see an oscillation of left and right bank as a result of the increased workload required in the lateral axis of the simulator, reduced visual cues, and insuffcent modeling of rotor IGE/OGE effects. The actual task demonstrated constant right wing down in a hover which increased with decreasing altitude.

6.9 Aural cueing proved to be a system that gave good performance in the simulation. The aural cueing was not a specific factor that the pilots commented on, however, the absence of aural cueing in the simulation drew instant complaint. The sound levels actually experienced in the aircraft where higher and more distinct than the cueing in the simulator. The aural cueing seemed to provide a low level background feedback to the pilots, on which they did not always consciously key, but on which deviations and anomalies were instantly detected.

6.10 The control feel of the simulator was evaluated by comparing the mechanical characteristics of the simulator with the aircraft. Differences in mechanical characteristics can be a contributor to differences in pilot workload required for similar tasks. Specifically, force gradient (force vs. displacement), deflection mapping, and system freeplay were compared. Although a quantitative analysis of the simulator has yet to be completed, some qualitative comments give a good indication of its mechanical characteristics. First, the test pilots indicated that the control mapping and control sense was indicative of the real aircraft, as were the characteristics of the power lever and pedals. However, the cyclic stick characteristics were incorrect, with the pilot noting that the cyclic stick in the simulator felt noticeably 'heavier'. A heavy stick would indicate greater breakout forces and a steeper force gradient. Additionally, simulator cyclic trim system freeplay was evident, yet *control system freeplay* was yet to be determined. If the trim system freeplay in the simulator exceeds the control system freeplay, the pilot could easily be making control inputs within the deadband, which would, in turn, drive up the workload.

6.11 The largest number of comments by the pilots were centered around the shipboard environment 'look and feel'. Altitude cues were not present in the simulation to the degree required, while during the actual evolution, altitude was easily and precisely determinable. The cause of this will be discussed later. Ship turbulence effects on the airframe were also lacking.

6.12 Aircraft procedures, such as pattern profile around the ship, very closely matched the actual requirements. This was perhaps the best simulated portion of the training, with one pilot commenting after his first landing "..I'd been here a thousand times before, it was just like the simulator."

6.13 The cockpit at the MFS uses actual aircraft hardware, to maximize a realistic environment and procedures. The cockpit environment must also properly induce realistic body forces on the pilot to give him the correct 'seat of the pants' cues. This is best done through a motion base, and a combination of active seat dynamics and a pilot g-suit. The simulation falls short here, since the training did not employ the motion base, seat shaker, or g-suit.

6.14 Visual detail is usually a product of hardware processing capability. Exact field of view simulation would be the most desired, which would include not only forward and overhead windows, but also chin windows. The visual images themselves are simply a matter of programming time to prepare them for use, and processor capabililty. Presently the V-22 simulation at NATC lacks cockpit chin bubbles and overheads due to the roll-in roll-out configuration of the system, but presents state-of-the-art ship visual models, which are being constantly upgraded.

6.15 The aerodynamic model of the simulator is quite important in reproducing reality. In this case we refer to the aerodynamics of the shipboard environment, the aerodynamics of the aircraft, and the interaction of the two. This is an extremely complicated issue which is under study by the US Navy and it's associated U.S. academic institutions, as well as the international community.

6.16 The two most significant of the problems discovered in the simulation during training were the airwake modeling in the near ship environment and the lack of visual cues in and around the shipboard region. For airwake modeling, two methods were examined during the course of the training. The first method attempted was a 'localized grid' method, in which a rectangular grid of ten by ten sections of airspace was mapped out to a range of one mile from the center of the ship deck. Each section was then assigned an up, down, and sideward 'base' air disturbance speed, and an acceptable plus-or-minus random component. When the aircraft center of gravity entered a region of turbulence, gust values were calculated for the block region by adding or subtracting the random component from the base values and then scaling the values based on altitude above the ship deck. These gust values were then included in the aircraft aerodynamic equations.

6.17 Transitions between grid frames were accomplished using a simple linear filter for each gust axis. Airflow velocities in each section were based on pilot experience, the limited flow visualizations that were available, and data gathered by the Dynamic Interface Department at the Naval Air Test Center. In practice, this modeling methodology did not provide an appropriate frequency and amplitude of pilot required responses, and the model was abandoned during the simulator training effectiveness evaluation phase prior to the onset of training. The basic reasoning behind the model continues to be examined.

6.18 Another, simpler method of airwake modeling was then used. This method simply raised the pilot workload by placing low frequency white noise into the control system inputs as a function of position relative to the landing spot. This computer generated disturbance raised the required pilot workload the level desired. This model noise was filtered out as the simulated aircraft transitioned over the deck edge, as the normal V-22 ground effect models were ramped in. This methodology caused several problems during the training and its utility is marginal at best. The problems encountered in this training have prompted several lines of study into bettering airwake models for the shipboard environment through various resources.

6.19 Shipboard visual cueing proved to be a significant problem area during training as well. The ship model used was upgraded in-house from the basic model provided with the visual generation system. The lack of a good sea surface and ship bow and stern wake models were found to be a problem early in the simulator evaluations, but no changes were implemented before training began. The ship model itself gave good visual cues during the final approach to hover portion of the pattern; but when the pilot's view was confined to the side of the ship superstructure and the flight deck during the final hover phase, the visual cues became less informative. The same problem was encountered during the extended portions of the flight pattern.

6.20 The sea surface model failed to provide good height cues to the aircrew and, even with 'ship' in sight, the pilot was forced to have the

copilot call altitudes or frequently scan inside the cockpit to read altitude. The addition of some aircraft support trucks and support equipment models on the flight deck surface helped provide cueing in the low hovers, but significant improvement remains to be made in this area.

6.21 The addition of ship water wake modeling and bow wave modeling to the visual scene provided a small measure of improvement during flight over water, in those regions of the pattern where the ship was in sight. Ship wakes helped provide the pilot with critical lineup cues. The Navy is improving the ship visuals by producing a very high detail amphibious assault ship model for further training which will incorporate many details of the ship, such as external walkways and ducting on the side of the ship superstructure, hatch-covers, and other features on the deck. A solution for the sea surface problem is still being investigated.

6.22 The six degree-of-freedom ship motion model was derived from actual test data. This model, when plotted against actual recorded ship motions, compared very well. During the training sessions, however, the pilots had trouble perceiving this projected motion, and the ship motion model had gains ranging from 1.5 to 3.0 placed on the six channels of output to boost the apparent motion. This perception problem appears to stem from the lack of visual cues on and around the flight deck area and the simple visual sea surface model, coupled with the training not taking place under platform motion. The ship motion model should serve very well once its precise outputs are no longer lost in the perceptual noise of the other cueing devices.

6.23 The ship motion model being added will be approximated by a second order forced oscillatory system, which produces a very characteristic resultant harmonic motion. Of course, the relative size, height, period, etc. of the oscillatory motion is influenced by many different variables; however, the basic shape of the curve (a modulated sine wave within a sine wave, offset by some non-zero trim value) always holds. Although much of actual ship oscillatory motion is based on statistical parameters and is undeniably random and unpredictable, very close approximations to the essentials of the motion can be derived. These motions are give by :

$$A = A_1 \cos(\omega_1 t + \phi_1) \cos(\omega_2 t + \phi_2) + A_2$$

or

$$A = A_1 [\cos(\omega_1 t + \phi_1) + \cos(\omega_2 t + \phi_2)] + A_2$$

where

A = Resultant displacement
A_1 = Maximum displacement amplitude
ω_1 = Modulating frequency
ϕ_1 = Modulating phase shift
ω_2 = Modulating frequency
ϕ_2 = Modulating phase shift
A_2 = Trim offset
t = time

Representative ship motion can be produced, with appropriate constants derived from truth data. Enclosure 1 provides a comparision of predicted ship roll motion with actual data. Since ship motion is a statistical phenomenon it cannot be explicitly copied. As shown in Enclosure 1, general trend agreement can be obtained.

6.24 The aircraft aerodynamic model and rotor model performed well for the mission training, but the lack of a blade element model in the simulation prevents the simulator from responding properly to a ship airwake model. Further investigation is required.

6.25 IGE and OGE aerodynamic models incorporated in the basic airframe model give good results for landbased training, but lack the sophistication and truth data required to simulate the one rotor IGE/one rotor OGE situation found during shipboard operations. It is hoped that data from the first ship trials will enable creation of such a model for the simulation training that will precede the next series of sea trials.

6.26 The landing gear model used in the V-22 simulation is an adaptation of the generic gear model used in all of our simulations, ranging from AV-8 to F/A-18 to the V-22 aircraft. Using this gear model in a slow vertical landing onto a six-degree of freedom deck regime was one of the biggest challenges in our training preparation. The breakout frictions required to keep the aircraft from sliding about the deck at idle power were noticeable to the pilots. Upon application of power by the pilot to taxi the aircraft, the aircraft would not move at all at low power settings. When a power setting 10-20% higher than that required in the real aircraft was reached, the simulation would 'breakout' and roll with a

perceptable jerk. Also, when landing on spots at the extreme aft of the ship, the gear damping would produce a heave motion 180 degrees out of phase with the ship motion.

6.27 Hardware also played a large role in the less effective areas of the training. The motion base was not used during this training. The motion algorithms developed in-house for the V-22 at the time were not fully verified, and the degree of confidence in them was low. Since the training has been completed, these algorithms have been refined and they have been used in subsequent training sessions. It is believed that use of the motion base will help the pilot perceive ship motion and airwake turbulence through body forces and provide helpful cues for hover work at the ship.

6.28 The simulation visual display system was hampered by the lack of a view through the chin windows of the aircraft. The V-22 simulator cockpit is equipped with these windows, but the confines of the motion base, and the requirement to keep the motion base usable for all the MFS simulations precludes the mounting of visual display devices for these windows. The lack of these windows, coupled with the low visual cues from the flight deck, created a higher workload situation during low hovers and landings in the simulation.

6.29 Computer processor time, in the form of time delays, also played a part in the training effectiveness of the simulator. The measured time delay in the system, from pilot stick step input to visual system update, was found to average 128 milliseconds greater than that experienced in the actual aircraft. The technology is in place today at the MFS to reduce the average time delay to 95 milliseconds with new computer hardware and modeling techniques. This would further improve the training effectiveness of the device by pushing simulator responses more toward the response times of the aircraft.

7.0 CONCLUSIONS

7.1 The overall training effectiveness of the simulator was qualitatively ranked by the test pilots as excellent. Most of the deficiencies made the simulator training tasks harder to perform than the actual event.

7.2 Pilots noted that the simulator, through task repetition, instills task discipline and familiarity and increases safety. The simulator, though lacking in some areas, gave the pilots an excellent first impression of the task. This early impression reduced the pilot's anxiety of conducting tasks in the aircraft, thereby reducing stress levels and improving pilot concentration and efficiency.

7.3 In terms of training, test pilots also commented that the ability to practice shipboard emergency situations, and the proper corresponding emergency procedures was invaluable. Some of the emergency situations trained for were : run-on landings, one engine inoperative landings, and wave-offs. Two of the situations trained for, the case of one gear failing to extend and wave-offs, were encountered during the test period and the pilots reacted as trained without further incident.

7.4 When a pilot flies a new aircraft type aboard ship for the first time, his initial landings and takeoffs normally display noticable aircraft attitude, control, and power deviations in frequency or in deflection during the approach profile, hover, and landing phases until the pilot feels comfortable with the aircraft and the shipboard environment. As revealed by time history data, in Enclosure 2, these deviations during initial landings and takeoffs were hardly evident during the V-22's initial shipboard trials due to effective pilot training.

7.5 Simulator preparation enabled the test team to define and perfect the 'control strategy' the pilots would use to get the tiltrotor aboard the ship. Because of the unique acceleration and deceleration capability of the tiltrotor, pilots had to develop new longitudinal control habits using articulating nacelle control. This habit pattern was developed in the simulator and verified during actual training flights. Without the benefits of a high fidelity simulation, flight training costs could easily have increased tenfold, with an attendant increase in risk.

7.6 We belive that use of the simulator enhanced safety of flight and no mishaps occurred during the actual test. This was a hazardous test in a prototype aircraft under demanding shipboard conditions. The fact that our test pilots conducted all launches and recoveries with precision can be attributed to a large degree to the effective simulator training.

8.0 FUTURE PLANS

8.1 As the developmental test and evaluation schedule of the aircraft progresses, there will once again be training at the Manned Flight Simulator in the shipboard environment for the next evolution at sea. For support of this effort, work focuses on several areas in the time allowed to improve the performance of the system.

8.2 The largest improvement will be found in the visual modeling area. A new amphibious assault ship model is being prepared which will contain eight times the number of polygons found in the previous model. This extra detail will be concentrated in the areas that the pilots have found need the most work, such as the side of the superstructure and the flight deck edge. An animated Landing Signalman Enlisted figure will be added. In addition, this model will be Night Vision Goggle compatible to support a broad spectrum of testing conditions. It is hoped that the visual model improvements will make the ship motion more apparent and use of the realistic, unaugmented ship motion model will become possible.

8.3 The landing gear model will be further tuned to give more realistic breakout and friction values as data becomes available. If the apparent ship motion becomes more readily detectable by the pilots, the more realistic ship motions will require less compensation in the gear modeling. The use of the motion base will give touchdown cues and strut deflection cues lacking in previous training.

8.4 The motion base will also be employed for this series of training. The algorithms were used successfully in the most recently completed training sessions. The increased cueing should upgrade the training effectiveness.

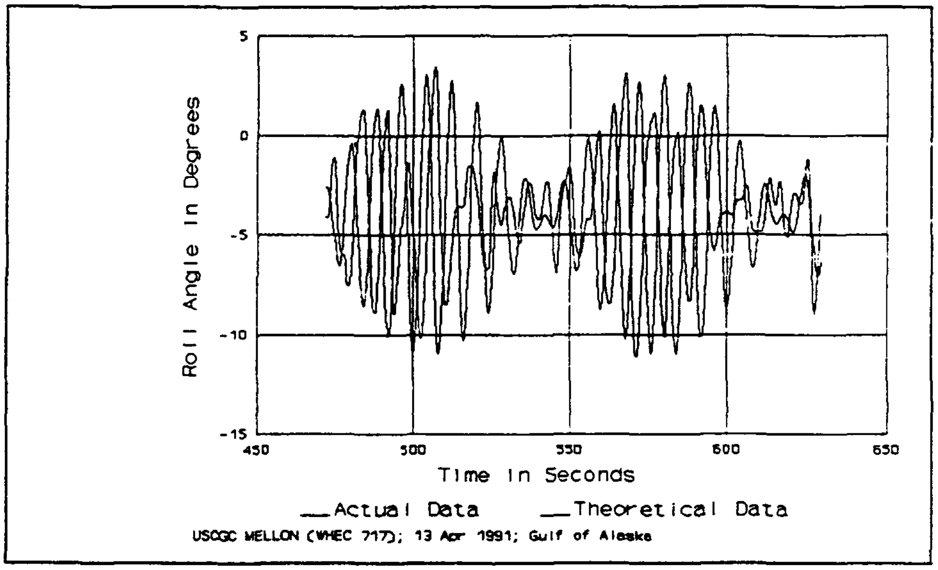
8.5 The V-22 simulation continues to provide excellent flight test support through constant upgrading and effort on the part of U.S. Navy personnel. This simulation capability is being employed in other applications not orginally planned such as; cockpit lighting studies, crew coordination studies, hardware reliability and maintainability studies; in addition the modular code designed for the trainer has been reused in a deployable aircrew coordination trainer and has provided data for the Operational Flight Trainers now under development.

8.6 By beginning the simulation effort very early in the aircraft life cycle and by constant upgrades to maintain configuration with the evolving aircraft, the NATC MFS has produced an effective and proven flight test support tool.

9.0 ACKNOWLEDGEMENTS

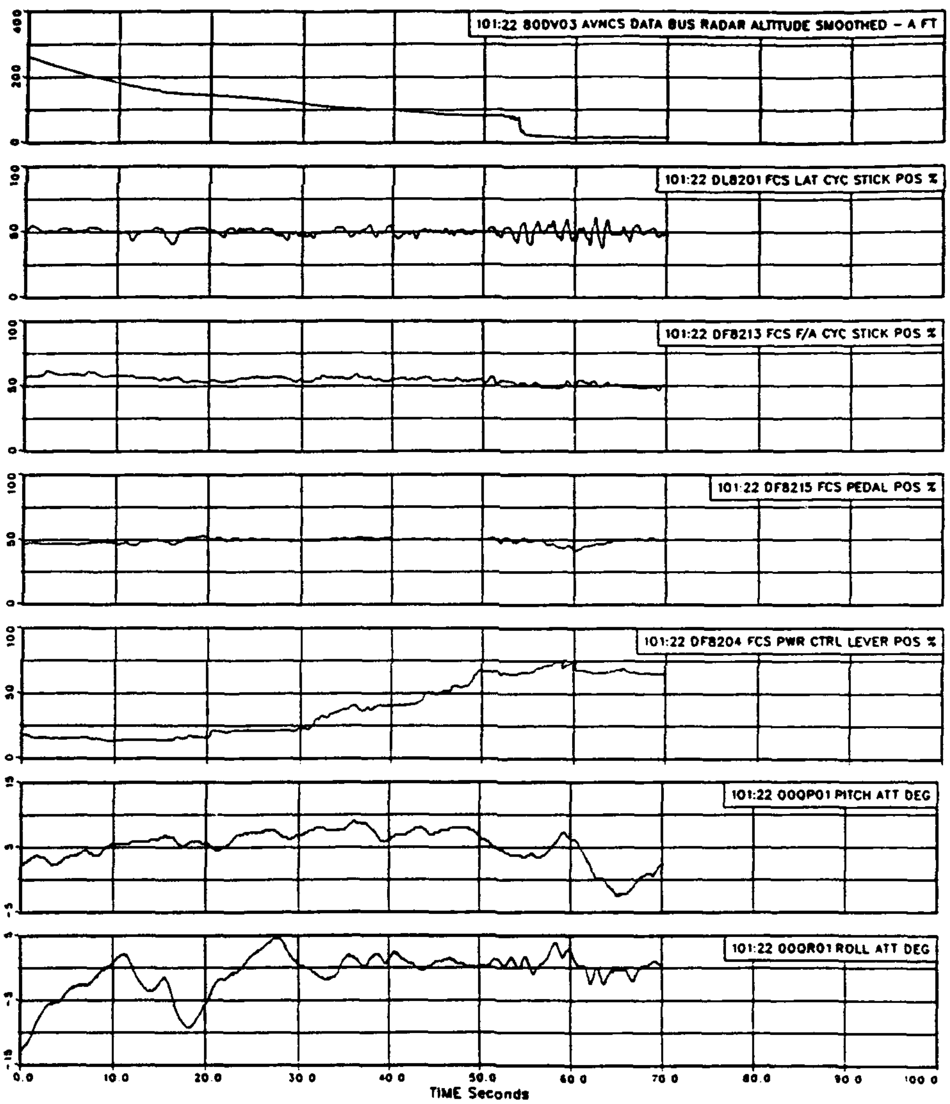
9.1 The authors of the paper would like to note that the simulation described above is the work of the many dedicated professionals at the Manned Flight Simulator facility. The following specific people should be recognized for their roles in the effective simulation training being discussed above : Mr. Kurt Long, Mr. Danny Campbell, Mr. Joe Kelponis and Mr. Mike Hughes. Mr. Jeff Weathers deserves special recognition for his work with the V-22 flight control laws.

9.2 Additionally, the leadership, dedication and foresight of the Naval Air Systems Command V-22 Program Manager, Colonel J. Schaefer (USMC), and the Assistant Program Manager, Major R. Curtis (USMC) in establishing and maintaining this simulation capability has been instrumental in the development of the V-22 Osprey.



Predicted vs Actual Ship Motion
Time History Data

Enclosure 1



Actual Flight Test Data
V-22 Shipboard Approach/Hover/Landing

Enclosure 2

UTILISATION D'UN SIMULATEUR DE RECHERCHE POUR LE DEVELOPPEMENT DE NOUVEAUX CONCEPTS DE COMMANDES DE VOL

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1. RESUME
Plusieurs études réalisées à l'ONERA ont montré l'utilité de tester le comportement de l'avion avec le pilote dans la boucle de pilotage en mettant en oeuvre un simulateur de recherche dès les premières étapes de la conception de nouveaux systèmes de pilotage destinés aux avions futurs. La communication présente trois études de concepts de commandes de vol spécifiques des phases de vol étudiées. La description de la phase d'élaboration des concepts avec ce simulateur de recherche et, pour deux d'entre eux, de la validation des solutions ainsi retenues sur des simulateurs de vol plus élaborés permet de conclure sur le rôle complémentaire de ces moyens d'essais.

2. ABSTRACT
Several studies performed at ONERA have shown the usefulness of testing the behaviour of the whole aircraft with the pilot in the loop by using a research flight simulator as soon as the preliminary design of new FCS for future aircraft is undertaken. The communication presents three conceptual studies related to mission oriented control systems which were performed at ONERA's research flight facility. The description of the conceptual phase of each of these studies and, for two of them, of their further validation on full flight simulators allows to conclude about the complementary roles of research and full flight simulators.

3. INTRODUCTION
La technologie du contrôle actif associée à des calculateurs de bord très rapides permet une réduction de la charge de travail du pilote. Ceci est réalisé par le développement de nouveaux concepts de commandes de vol plus spécifiques de la mission de l'avion que précédemment. Avec de tels systèmes, le pilote contrôle les paramètres de l'appareil qui sont directement associés à la phase de vol à réaliser au travers d'un mini-manche. Quant au calculateur de bord, il calcule les meilleurs braquages des gouvernes nécessaires à la demande du pilote en assurant néanmoins la sécurité du vol (stabilité de l'appareil et contraintes liées à la présence du pilote et/ou de passagers).

Plusieurs études réalisées à l'ONERA ont montré l'utilité de tester le comportement de l'avion avec le pilote dans la boucle de pilotage en mettant en oeuvre un simulateur de recherche dès les premières étapes de la conception de nouveaux systèmes de commandes de vol destinés aux avions futurs. Ce simulateur de vol à base fixe, muni d'un environnement d'avion très dépouillé, a permis d'essayer de nombreux modes de pilotage candidats à la réalisation de phases de vol particulières et de selectionner les meilleurs en vue de leur évaluation ultérieure sur des simulateurs de vol plus complets.

La communication présente trois études de concepts de commandes de vol développées à l'Office:

a. un système intégré de commandes de vol et de conduite de tir canon Air-Sol pour lequel le pilote commande directement le point d'impact instantané des projectiles pendant la phase finale de l'attaque au travers de son mini-manche,

b. un concept de commandes de vol principales pour le vol longitudinal des futurs avions de transport en phase finale d'atterrissage; la commutation du système de commandes principales sur des lois de secours moins évoluées en cas de panne a également été examinée. Cette étude a été réalisée sous les auspices du GARTEUR en collaboration avec d'autres organismes de recherches (RAE, NLR, DLR),

c. un concept de commandes de vol complet (longitudinal et latéral) pour les mêmes avions que dans l'étude précitée.

La description des différentes phases d'étude de chacun des concepts et, pour les deux derniers, de la validation sur des simulateurs à base mobile plus complets des solutions mises au point à l'aide du simulateur de recherche permet de conclure sur les rôles complémentaires de ces deux types de simulation pendant le déve.oppement de nouveaux systèmes de commandes de vol.

4. SIMULATEUR DE RECHERCHE DE L'ONERA
Un simulateur de vol à base fixe existe à l'ONERA/-Chatillon depuis plusieurs années. Ce moyen a été développé en vue de répondre à la nécessité impérieuse de prendre en compte la présence de l'homme dans la boucle de pilotage dès le stade préliminaire de la définition de nouveaux concepts de commande. Ceci est réalisé par l'utilisation d'un environnement suffisamment réaliste pour assurer la crédibilité des simulations mais néanmoins aisé à mettre en oeuvre et surtout très convivial [1].

Ce simulateur est, pour l'essentiel, composé d'un ordinateur hôte sur lequel est branché un ensemble de matériels permettant l'acquisition, les calculs et le dépouillement d'un essai complet ainsi que d'une cabine

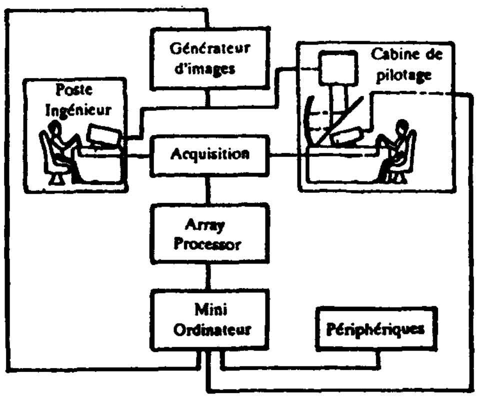


Figure 1 : Boucle de simulation.

de pilotage fixe couplée à un système de visualisation simplifié (figure 1).

L'opérateur dispose d'un mini-manche, d'un palonnier réglable, d'un bloc de manettes des gaz et d'un tableau d'interrupteurs à usages multiples (changement de configuration, gestion de la simulation,...).

Le système de visualisation est composé d'un paysage synthétique en vision crépusculaire ou "tête haute" et d'un tableau de bord simplifié ou "tête basse".

En tête haute, l'image synthétique du paysage extérieur est rejetée à l'infini au moyen d'un dispositif optique approprié. Trois scènes de 120 km par 120 km sont actuellement disponibles à l'Office :

a. une scène standard avec une piste d'atterrissage,
b. une scène Air-Sol avec des massifs montagneux,
c. une scène Air-Air avec la représentation d'un avion cible.

De plus, l'utilisateur peut superposer à cette image synthétique des informations relatives aux paramètres de fonctionnement de l'appareil (collimateur tête haute) au moyen d'un ensemble de réticules programmables dans le plan de vision (figure 2).

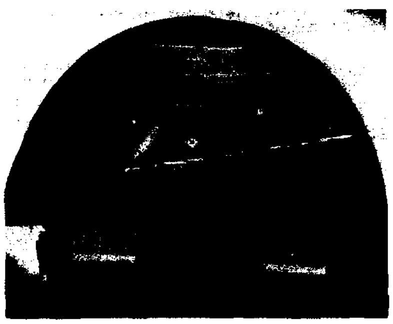
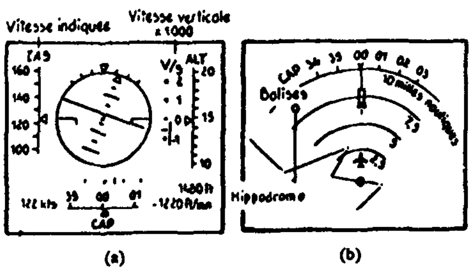


Figure 2 :Image synthétique et collimateur tête haute.

En tête basse, deux tubes cathodiques monochromes programmables placés devant le pilote présentent des informations de pilotage (figure 3). L'un simule un tableau de bord simplifié (EADI : Electronic Attitude Display Indicator) avec les indications de l'altimètre, du variomètre et de l'horizon artificiel,.... L'autre représente la vue de dessus du paysage survolé mobile par rapport à un symbole fixe désignant l'avion (EHSI : Electronic Horizontal Display Indicator).



(a) (b)

Figure 3 : Visualisation tête basse - (a) Primary Flight Display - (b) Map Display.

En outre, un "poste ingénieur" comprenant un ensemble restreint de commandes et un répétiteur d'images sur écran graphique permet au responsable de la simulation de suivre l'essai ou d'y participer (combat aérien).

Pour permettre le déroulement et l'analyse des simulations, un certain nombre de logiciels ont été développés. La structure modulaire de ces logiciels écrits en FORTRAN sur l'ordinateur hôte et sur un calculateur parallèle AP120B géré par celui ci (le respect de la cadence de 25 images par secondes nécessite d'intégrer les équations de la mécanique du vol très rapidement) permet d'implanter quasiment tout type d'aéronefs. Actuellement trois modèles d'avion sont disponibles:

a. un avion de combat type,
b. un autre avion de combat type muni de lois de pilotage pour le tir air sol,
c. un avion de transport lourd typique d'un AIRBUS muni de lois de pilotage pour l'atterrissage.

Les utilisateurs de cette installation sont les ingénieurs chargés de la conception des lois de commandes de vol et les pilotes invités à venir donner leur avis sur les choix préliminaires retenus.

5. CONDUITE DE TIR CANON AIR-SOL

Parmi les tâches de pilotage, le tir canon air-sol est l'une des plus difficiles en raison du temps très court imparti pour la visée et des dangers présentés par la proximité du sol et la défense anti-aérienne adverse. La qualité du résultat est étroitement dépendante du bon fonctionnement de la chaîne pilote-lois de pilotage-conduite de tir.

L'utilisation d'une conduite de tir du type CCPI (calcul continu du point d'impact) permet essentiellement d'accroître la fenêtre de tir. Le point d'impact (PI) des obus au sol est calculé à partir des mesures de distance, d'incidence, de dérapage et des variables d'attitude de l'avion. La conduite de tir fournit également une indication sur le déplacement prévisible du point d'impact en fonction des évolutions de l'avion.

L'objectif de cette étude est de définir et de valider de nouveaux concepts de pilotage de nature à faciliter cette phase de vol et à accroître son efficacité.

5.1 Concepts de pilotage

Pour améliorer le pilotage de l'avion pendant la phase de tir air-sol, trois concepts ont été examinés.

5.1.1 Force latérale directe [2]

Dans les opérations de tir classique (viseur à hausse fixe), le pilote ne dispose que de quelques secondes pour identifier l'objectif, pointer son avion à gîte et dérapage nul, tirer et s'échapper. Sur un avion conventionnel, le pilote peut éprouver des difficultés à réaliser le pointage dans de bonnes conditions car l'alignement sur la cible, en latéral, requiert précisément l'utilisation du gîte et du dérapage. L'introduction d'une gouverne supplémentaire de force latérale directe est de nature à faciliter cette phase de vol puisqu'elle autorise dès lors le maintien du vecteur vitesse dans le plan de symétrie de l'appareil (vol à dérapage nul).

5.1.2 Pilotage par objectif de l'appareil

La notion de pilotage par objectif signifie que le pilote ne pilote plus directement les débattements des gouvernes. Il commande des ordres évolués de pilotage, appelés modes supérieurs ou objectifs, qui sont en relation directe avec les paramètres caractéristiques de la trajectoire que le pilote désire contrôler. C'est le calculateur qui a la charge d'élaborer les ordres de braquage des gouvernes de façon à réaliser les ordres fixés par le pilote.

Dans cette application, le pilotage par objectif est limité au contrôle latéral de l'avion muni d'une gouverne de force latérale directe. Le pilote agit directement, avec

une dynamique choisie, et de façon découplée sur les vitesses de roulis (au manche) et de lacet (avec le palonnier) ainsi que sur un mode de pointage par translation latérale ou par rotation de type tourelle de l'appareil au moyen d'une commande supplémentaire (joystick) installée sur la manche. La pureté du comportement de l'avion ainsi obtenu devrait faciliter la tâche du pilote.

5.1.3 Pilotage du point d'impact des obus
Cette nouvelle application du pilotage par objectif met à la disposition du pilote des variables de commande directement associées à la visée, en l'occurrence la position du point d'impact des obus au sol (figure 4).

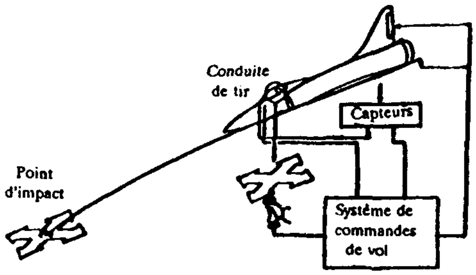


Figure 4 : Pilotage du point d'impact des obus.

Il semble en effet qu'un tel système de commande doit être de nature à réduire de façon significative la charge de travail du pilote et augmenter la précision de la visée. Ce concept intègre un régulateur de tir et un régulateur de pilotage à une conduite de tir (figure 5). Il peut donner lieu à une grande variété de modes de

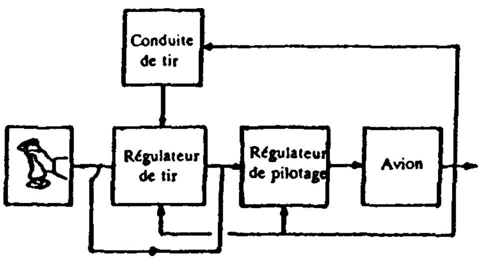


Figure 5 :Architecture du système de commande.

pilotage. Cependant, la dissimilitude de ces nouveaux modes par rapport aux modes de pilotage classiques doit rester acceptable pour les pilotes. Compte tenu de ces éléments, trois modes ont été élaborés:

a. mode 1: le déplacement du point d'impact est commandé dans les axes liés à l'avion. Une action sur le manche en "profondeur" commande une vitesse de déplacement dans le plan de symétrie de l'avion. Une action sur le manche en "gauchissement" commande une vitesse de déplacement dans un plan perpendiculaire au plan de symétrie et un angle de gîte désiré lorsque le déplacement devient important. Le palonnier n'est pas utilisé.
b. mode 2: même principe que précédemment mais le déplacement du point d'impact est commandé dans les axes liés au sol.
c. mode 3: le déplacement du point d'impact est commandé dans les axes avion par des actions sur le manche en "profondeur" et sur le palonnier. En "gauchissement", le manche commande une vitesse de roulis.

5.2 Modèles d'avion
Pour évaluer ces concepts, quatre modèles d'avion de combat typiques ont été utilisés:

a. l'avion N, avec un pilotage conventionnel et un dispositif d'augmentation de la stabilité,
b. l'avion A, identique au précédent, avec le pilotage du point d'impact,
c. l'avion Y1, avec une gouverne de force latérale directe et le pilotage par objectifs du mouvement latéral de l'avion,
d. l'avion Y2, avec le pilotage du point d'impact et le maintien du dérapage nul au moyen de la gouverne de force latérale directe.

5.3 Essais Préliminaires au CEV d'Istres [3,4]
Au début de cette étude, l'ONERA ne disposait pas du simulateur de recherche décrit au paragraphe 4. Seul un calculateur analogique "équipé en simulateur" permettait à l'époque d'évaluer des lois de pilotage [2]. Devant la faiblesse de ce moyen de simulation, la première évaluation de ces différents concepts a été réalisée au CEV d'Istres.

5.3.1 Installation d'essais
L'installation utilisée est un simulateur à base fixe comprenant une cabine d'avion de combat monoplace équipée d'une configuration de cockpit voisine de celle du Mirage 2000 en ce qui concerne le tableau de bord, le viseur et les commandes de vol. Seule la poignée de manche a été remplacée par un équipement fourni par l'ONERA. La visualisation du paysage extérieur de la cabine provient de l'image d'une maquette de paysage filmée en vidéo.

5.3.2 Configurations essayées
Cinq configurations ont été retenues pour ces premiers essais:

a. l'avion N,
b. l'avion Y1 et le mode de translation latérale,
c. l'avion Y1 et le mode tourelle,
d. l'avion Y2 et le pilotage manuel du point d'impact,
e. l'avion Y2 et le pilotage automatique du point d'impact.

Pour chaque configuration, la loi de pilotage a été réalisée en faisant l'hypothèse que le système à contrôler était linéaire.

5.3.3 Essais
Les essais ont comporté la phase d'acquisition fine de la (des) cible(s) en initialisant la trajectoire à une distance de 4 à 5 NM dans l'axe de la passe de tir, la phase de correction de visée avant le tir proprement dit et l'évasive. Ils ont été réalisés avec des conditions d'environnement diverses (vent et turbulence).

5.3.4 Résultats
L'exploitation des essais a été élaborée à partir des commentaires des pilotes et de leurs scores.

Cette première expérience au simulateur du CEV d'Istres a mis en évidence l'intérêt du pilotage par objectif par rapport au pilotage classique. Le pilotage manuel du point d'impact a été le plus apprécié. En revanche, le mode automatique a été très rapidement éliminé. Enfin, elle a surtout indiqué les caractéristiques que devait posséder une commande bien adaptée au tir canon air-sol:

a. acquisition initiale facile (amortissement et rapidité) avec la commande du manche, l'inclinaison de l'appareil pouvant être importante,
b. acquisition finale facile avec la même commande du manche, le mode d'alignement "ailes horizontales" "étant particulièrement efficace,

c. utilisation du palonnier non souhaitée pendant l'acquisition finale (avion Y1),
d. pas d'introduction d'une commande supplémentaire sur le manche (hésitation des pilotes pour choisir les commandes adéquates: avion Y1),
e. amélioration des lois de pilotage quand on s'écarte de l'hypothèse de linéarité du système.

A l'issue des simulations au CEV d'Istres, il est apparu que les modes de pilotage 2) et 3) n'emporteraient pas l'adhésion des pilotes. Seul le pilotage du point d'impact (mode 1) semblait donc être en mesure de convenir, sous réserve de l'améliorer.

5.4 Essais à l'ONERA [5,6]
En vue d'affiner plus utilement l'analyse de ce nouveau concept et de conclure sur l'intérêt des gouvernes de force latérale directe pendant cette phase de vol, des essais à l'ONERA ont été envisagés.

Face à la richesse des renseignements susceptibles d'être fournis par des simulations pilotées de bonne qualité, l'ONERA décida de se doter du simulateur de recherche décrit au paragraphe 4 en remplacement d'un matériel devenu obsolète.

5.4.1 Amélioration des lois de pilotage
La formulation mathématique détaillée des lois du régulateur de tir et du régulateur de pilotage est présentée dans [7]. On rappelle seulement que ces lois sont non linéaires et qu'elles assurent un découplage algébrique strict des différentes paires d'entrées-sorties [8]. Ainsi, les non-linéarités de la cinématique de la ligne de visée d'une part et celles de la dynamique de l'avion d'autre part sont éliminées algébriquement par ces lois. Une des conséquences est que le pilotage de la ligne de visée est pur et découplé quelle que soit l'inclinaison de l'avion.

5.4.2 Configurations essayées
Trois configurations ont été essayées lors de cette campagne:
a. l'avion N afin de valider le simulateur avec un avion muni de lois de pilotage classiques,
b. l'avion A avec le pilotage du point d'impact mais sans gouverne de force directe,
c. l'avion Y2 avec le pilotage manuel du point d'impact et le maintien du dérapage nul.

5.4.3 Essais
Les passes de tir proposées aux pilotes étaient plus complètes que celles réalisées à Istres puisque l'avion était en dehors de l'axe de la passe de tir au début des simulations (figure 6).

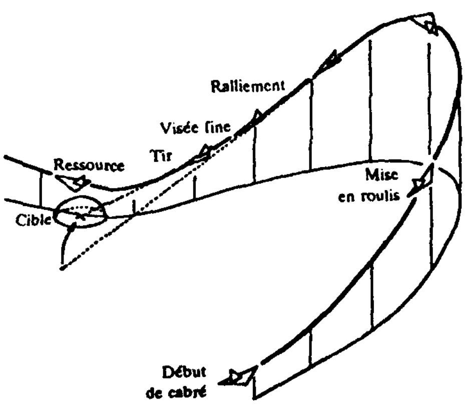


Figure 6 : Passe de tir air sol.

Les essais ont été effectués par des pilotes militaires dans des conditions d'environnement voisines de celles adoptées à Istres. Leur exploitation a été basée sur des éléments subjectifs (commentaires des pilotes) et sur des éléments objectifs (tracés graphiques, statistiques sur les coups au but, ...).

5.4.4 Résultats
Les résultats obtenus au cours de cette campagne d'essais sont les suivants:

a. Les commentaires de pilotes sont toujours très favorables à l'égard du mode de pilotage du point d'impact (avions A et Y2) par rapport à l'utilisation d'une conduite de tir conventionnelle. La charge de travail est nettement diminuée, surtout dans la correction des écarts latéraux. De plus, l'amélioration des conditions de tir est spectaculaire par forte turbulence; tout écart d'alignement observé est contré rapidement (figure 7).

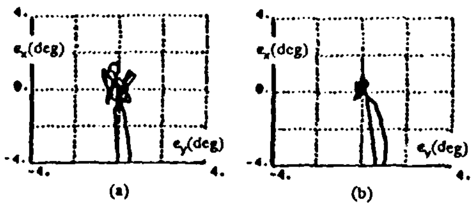


Figure 7 : Evolution des écarts de visée - (a) pilotage classique - (b) pilotage du point d'impact.

b. La charge de travail avec l'avion Y2 est sensiblement la même que celle observée avec l'avion A. En présence d'un vent de travers l'avion Y2 garde la possibilité de s'aligner *ailes horizontales tout en* conservant le dérapage nul grâce à la gouverne de force directe. La précision du point d'impact est ainsi améliorée. Cependant, l'évaluation de l'intérêt de la force latérale directe mérite surement d'affiner les résultats en s'assurant notamment que des effets pervers ne viennent pas biaiser le comportement de cet appareil hypothétique.
c. Bien que la possibilité de s'aligner sur les cibles avec les ailes horizontales ait été trouvée satisfaisante pendant la tâche de désignement de plusieurs cibles au cours d'une même passe de tir, il a été constaté que les pilotes *préféraient* souvent accélérer l'alignement sur les cibles par une mise en roulis afin de disposer de plus de temps pour faire les corrections finales.
d. Les différents commentaires faits par les pilotes ont généralement été confirmés par le dépouillement des enregistrements d'indices de performance divers

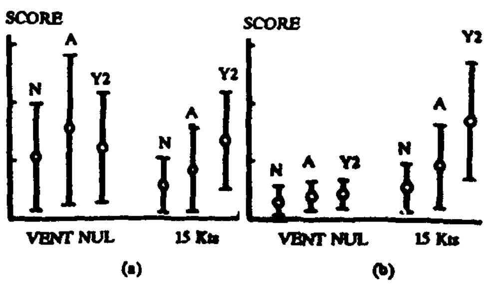


Figure 8 : Comparaison des scores sous turbulence - (a) moyenne - (b) forte.

(erreur de visée, distance de tir, ...). En particulier, les scores réalisés avec les avions N, A et Y2 pour plusieurs conditions de vent et de turbulence avec un scénario de tir sur deux cibles (figure 8) sont meilleurs dans tous les cas pour les appareils A et Y2 avec seulement un léger avantage à l'avion muni de force latérale directe. Cependant, il est à noter que la dispersion des résultats est relativement importante en raison du nombre limité d'essais effectués.

5.5 Conclusion
Face à de nouveaux concepts susceptibles de multiples réalisations, une première campagne de simulations pilotées au CEV d'Istres, dans un environnement très réaliste, a permis de dégager rapidement les voies dans lesquelles il convenait de poursuivre l'effort. Ensuite, après avoir retrouvé les mêmes résultats sur le simulateur de l'ONERA, le validant par la même, l'affinement du concept a pu être poursuivi.

A l'issue de ces travaux déjà anciens (1986) et dans la mesure où le tir air-sol au canon garde un intérêt pour les avions de combat futurs, il apparaîtrait naturellement essentiel de retourner sur le simulateur de vol du CEV d'Istres pour enfin conclure finement sur les objectifs de l'étude (à moins que, dans l'intervalle, d'autres études aient pu apporter un jugement définitif).

6. QUALITES DE VOL LONGITUDINAL POUR LES AVIONS DE TRANSPORT FUTURS

Les travaux présentés dans ce paragraphe ont été réalisés dans le cadre d'une étude conduite sous l'égide d'un groupe d'action du GARTEUR (Group for Aeronautical Research and Technology in EURope) en collaboration avec plusieurs organismes de recherche Européens (NLR, RAE, DLR, ONERA). Certains aspects de ces travaux ont déjà été publiés dans [9 et 10].

6.1 Objet de l'étude
Il s'agissait de caractériser, au moyen de simulations pilotées, les qualités de vol des avions de transport munis de lois de commandes évoluées et d'un collimateur tête haute en vue de définir des critères de conception des chaînes de pilotage des avions futurs bénéficiant des progrès liés à la commande active. L'étude portait plus précisément sur les modifications des qualités de vol longitudinal observées, en cas de panne, lors du remplacement des lois principales par un système de pilotage de secours pendant la phase d'atterrissage.

6.2 Essais préliminaires à l'ONERA
Le déroulement de l'étude comportait des essais préliminaires sur le simulateur de l'ONERA pour définir les lois de pilotage avant d'entreprendre la campagne de simulations au simulateur à base mobile du NLR.

6.2.1 Modèle d'avion
Le modèle utilisé est celui d'un avion de transport typique de 80 tonnes dérivé d'un modèle de type Airbus. Ce modèle est supposé instable longitudinalement en boucle ouverte. Il est équipé des lois de pilotage définies ci-dessous.

6.2.2 Lois de pilotage
Le contrôle longitudinal est une commande en "dérivée de pente/tenue de pente" pour laquelle les pilotes ont plusieurs jeux de gains à tester. Une automanette assure, au choix, le maintien d'une vitesse de référence ou de la vitesse instantanée. Cette loi de pilotage longitudinale sera nommée loi A dans la suite du texte.

Le contrôle latéral est une commande en "taux de roulis/maintien du gîte". Il présente également les caractéristiques suivantes:

a. coordination du virage au moyen d'une interconnexion ailerons-palonnier,
b. compensation en virage (tenue de la pente désirée pendant un virage),
c. retour ailes horizontales lorsque l'inclinaison latérale de l'appareil est inférieure à 3 degrés.

N'étant pas l'objet de l'étude, cette loi de pilotage latérale développée pour conférer à l'avion de bonnes qualité de vol transversal ne sera pas modifiée ultérieurement.

6.2.3 Installation d'essais
Le poste de pilotage est équipé d'un mini-manche provenant du NLR et placé à la droite du pilote. Une boite d'interrupteurs permet de changer de configuration pendant la simulation. En fonctionnement normal, le collimateur tête haute comprend (figure 9):

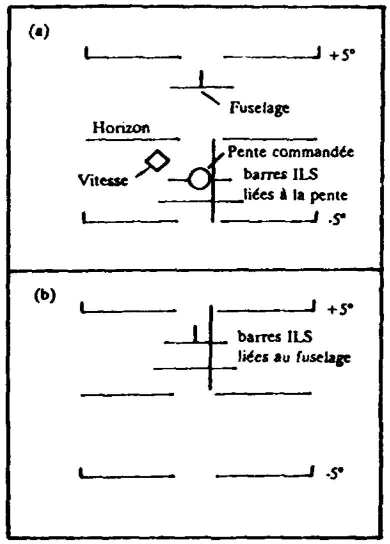


Figure 9 : Collimateur tête haute pour l'étude GARTEUR à l'ONERA - (a) principal - (b) de secours.

a. une échelle d'assiette matérialisée par trois barres formant les horizons principal et secondaires à +5 et -5 degrés,
b. une référence fuselage,
c. un vecteur vitesse sol (cercle à ailettes),
d. la pente commandée (losange),
e. des axes ILS (Instrument Landing System).

Les indications de la pente commandée et de la vitesse sol disparaissent dès qu'une "panne" survient et que le système commute sur la loi de pilotage de secours.

6.2.4 Conditions d'essais
L'avion étant sur une trajectoire d'attente en vent arrière, la tâche de pilotage consiste à rallier le faisceau ILS, à réaliser l'approche ILS, l'arrondi et l'atterrissage. En cas de difficulté pendant la phase finale de l'approche, le pilote à la possibilité de remettre les gaz et de rejoindre la trajectoire d'attente initiale (figure 10).

Les conditions météorologiques sont choisies par l'ingénieur d'essais. Il a le choix parmi trois profils de vent et deux niveaux de turbulence. La visibilité peut également être modifiée. Suivant la hauteur du plafond, le pilote réalise l'ensemble de son approche à vue (VMC) ou bien est obligé de voler aux instruments

(IMC) jusqu'à la base des nuages (500 ft).

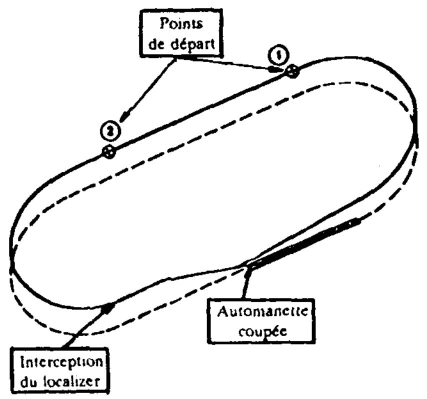


Figure 10 : Etude GARTEUR - Tâche de pilotage.

Pendant chaque essai, les commentaires du pilote et tous les paramètres de vol sont enregistrés en vue d'un dépouillement ultérieur. A l'issue de chaque essai, le pilote doit également remplir un questionnaire destiné à replacer ses impressions dans le cadre de l'échelle de Cooper-Harper. Toutes ces données sont consignées dans [11].

6.2.5 Première série d'essais
Six pilotes venant des quatre pays participant à cette opération GARTEUR participèrent à cette première série d'essais. Les résultats obtenus sont les suivants :

a. les pilotes doivent s'adapter à ce nouveau mode de pilotage pour lequel il faut agir par impulsion sur la commande et laisser la loi de pilotage réaliser sa tâche. Le contrôle de la pente de la trajectoire a généralement été jugé acceptable. En revanche, ce principe a été contesté pour l'arrondi, l'atterrissage et la montée; phases pendant lesquelles le contrôle de l'attitude est essentiel,
b. malgré le nombre de jeux de gains essayés, la loi a été estimée trop sensible. En particulier, les variations importantes de l'assiette longitudinale pendant les essais risquent d'entraîner une sensation d'inconfort pour les passagers,
c. l'ensemble des pilotes a estimé que le mouvement de la cabine était essentiel pour affiner leur jugement. Après une période de familiarisation, l'utilité du collimateur tête haute a été reconnue. A cette occasion, il été regretté que les limitations techniques de l'installation ne puissent permettre l'introduction de paramètres de vol supplémentaires. Cette restriction devrait être levée sur le simulateur du NLR.

6.2.6 Deuxième série d'essais
Compte tenu des remarques formulées par les pilotes, la loi A a été modifiée notamment pour réduire les excursions de l'assiette et pour introduire un mode d'arrondi privilégiant le contrôle d'une combinaison de la vitesse de tangage et de l'accélération normale lorsque l'altitude est inférieure à 30,5 mètres. De plus, pour répondre aux objectifs de l'étude, une loi longitudinale de secours avec deux jeux de gains (lois C et D) a été conçue en vue de conférer à l'avion un bon comportement en cas de "panne" de la chaîne de pilotage principale. Elle est constituée d'un contrôle de la vitesse de tangage. Elle n'utilise pas d'auto-manette. De plus, les gains de cette loi rustique ne varient pas avec la vitesse de vol en vue d'utiliser le minimum de capteurs.

Parallèlement à cette modification de la loi A, une nouvelle loi, appelée loi B, a été développée. Fondée sur les mêmes principes que la loi précédente, elle est censée procurer une évolution plus "continue" du symbole de la pente commandée dans le collimateur tête haute. En cas de "panne", cette loi est abandonnée au profit de la loi de secours (loi C) décrite plus haut.

Cinq pilotes ont participé à cette nouvelle phase de simulations avec les nouvelles lois A et B. Les résultats obtenus sont les suivants :

a. tous les pilotes ont estimé que les deux lois étaient acceptables avec cependant une préférence pour la loi B. En particulier le déplacement "continu" du symbole de la pente commandée a été très apprécié,
b. le passage du contrôle de la pente à la loi d'arrondi n'a posé aucun problème et a semblé tout à fait naturel,
c. la transition entre les lois principales et la loi de secours a été diversement appréciée. Plusieurs pilotes se sont plaints de la disparition de l'auto-manette et du manque de compensation de l'assiette longitudinale lorsque la poussée change,
d. les pilotes ont regretté le manque d'informations concernant le mouvement transversal de l'appareil, les indications d'altitude et de cap dans le collimateur tête haute.

A l'issue de cette deuxième série d'essais, il a été considéré que les lois de pilotage développées avaient atteint un niveau de qualité suffisant pour passer à l'étape suivante de simulations sur les installations du NLR.

6.3 Essais au NLR
6.3.1 Modèle d'avion
Le modèle d'avion adopté pour ces essais est différent de celui utilisé à l'ONERA. Il est dérivé d'un modèle de Boeing 747 allégé, rendu instable longitudinalement, et possédant les mêmes caractéristiques d'approche que le modèle de l'ONERA.

6.3.2 Lois de pilotage
Les lois de pilotage sont les mêmes que celles essayées à l'ONERA à la différence près de quelques gains qu'il a fallu adapter au nouveau modèle d'avion. A noter également que les deux jeux de gains de la loi de secours (lois C et D) seront testés pendant cette campagne d'essais.

6.3.3 Simulateur du NLR
Le simulateur du NLR est un simulateur à base mobile à quatre degrés de liberté. La cabine représente l'intérieur du poste de pilotage d'un avion de transport avec un équipage de trois personnes. Elle est équipée d'un mini-manche et d'un tableau de bord expérimental (EFIS) en place pilote.

Le collimateur tête haute (figure 11) est dérivé de celui utilisé à l'ONERA avec néanmoins des indications supplémentaires (glide à -3 degrés, cap, piste synthétique). Le nombre de symbole change pendant l'arrondi. D'autre part, il est considéré que les indications du collimateur tête haute et du tableau de bord expérimental disparaissent lorsque survient une "panne".

Le paysage extérieur est produit par une caméra se déplaçant au dessus d'une maquette de paysage (image en plein jour).

6.3.4 Conditions d'essais
La tâche de pilotage est la même que pour les essais à l'ONERA mais la "panne" est annoncée par un signal sonore que le pilote doit interrompre avant de poursuivre sur l'une des loi de secours.

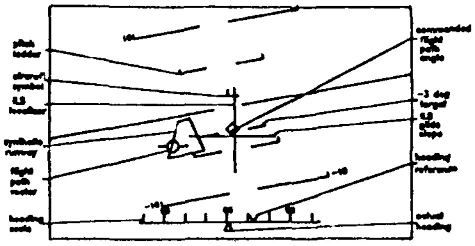


Figure 11 : Etude GARTEUR - Collimateur tête haute du NLR.

Les conditions météorologiques comportent plusieurs profils de vent et deux niveaux de turbulence. Le temps est nuageux et le plafond est à 152.4 mètres (500 ft) du sol.

Les essais ont porté sur les quatre combinaisons possibles avec les deux lois principales et les deux lois de secours. Pendant chaque essai, les paramètres de vol et les commentaires des pilotes sont enregistrés. A la fin de chaque essai les pilotes donnent une note (dans l'échelle de Cooper-Harper) pour la loi principale et la loi de secours testées.

6.3.5 Essais
Quatre pilotes venant des quatre pays participant à l'opération GARTEUR réalisèrent les essais. Les résultats obtenus ont été les suivants:

a. bien que les lois A et B aient été conçues pour être de niveau 1, seule la loi B a constamment été considérée de niveau 1 en raison de problèmes sur la symbologie en tête haute pour la loi A,
b. les lois de secours ont, dans l'ensemble, satisfait les pilotes. Elles ont néanmoins été considérées de niveau 2 étant donnée la soudaineté de la modification de la charge de travail quand la "panne" survient,
c. l'estimation des qualités de vol est tributaire des informations présentées au pilote et aussi du comportement latéral de l'appareil.

6.3.6 Conclusion
Il est hors de propos de revenir ici sur les conclusions, dégagées par les membres du GARTEUR, relatives à la caractérisation des qualités de vol pour la conception des systèmes de commandes de vol électriques pour les avions de transport futurs [10].

Du point de vue de l'utilisation complémentaire d'installations de simulation très différentes, il convient de remarquer le rôle important des essais réalisés à l'ONERA pour définir de "bonnes" lois de pilotage et la symbologie du collimateur tête haute malgré les limitations techniques de l'installation. Une fois ce travail préliminaire achevé, les simulations au NLR ont pu être réalisées aisément sans rencontrer de problèmes majeurs.

7. APPROCHE METHODOLOGIQUE POUR LA CONCEPTION DE COMMANDES DE VOL

L'objectif de cette étude est de développer une approche méthodologique pour la détermination de modes supérieurs de pilotage adaptés à la réalisation de la phase d'approche et d'atterrissage d'un avion de transport futur à commandes de vol électriques.

Après avoir effectué un recensement des combinaisons de modes de pilotage envisageables, la méthodologie mise au point à l'ONERA a permis de choisir celles susceptibles de remplir réellement la tâche de pilotage impartie. Les lois de pilotage ainsi retenues, réglées pour satisfaire les critères classiques de qualité de vol, ont été essayées tout d'abord au simulateur de l'ONERA. Ensuite, la meilleure des lois a été testée au simulateur à base mobile du CEV/d'Istres.

7.1 Démarche méthodologique
L'idée directrice de ce travail est que le pilote souhaite commander directement, et le plus simplement possible, les paramètres critiques, appelés modes supérieurs de pilotage ou objectifs de pilotage, pour le bon achèvement de la phase de vol considérée. Il est à noter que le concept de tir air-sol développé à l'ONERA procède d'une démarche similaire.

7.1.1 Critères de choix des objectifs
La synthèse des lois de pilotage par objectifs repose sur les considérations suivantes:

a. Compte tenu de la phase de vol envisagée, le système dynamique mécanique du vol plus commandes de vol est supposé linéaire,
b. Le pilote a, en général, plusieurs objectifs à réaliser en même temps. Afin de lui faciliter la tâche, on impose que les objectifs de pilotage ont peu ou pas d'interaction entre eux (figure 12). C'est à dire que

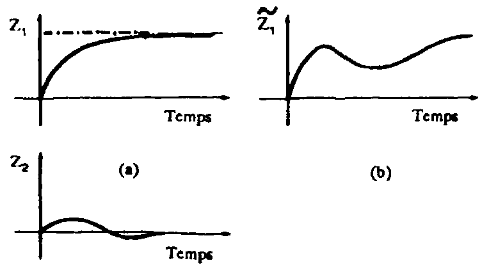


Figure 12 : Illustration du découplage des modes de pilotage - (a) modes désirés - (b) variable non commandée.

si le pilote modifie sa demande sur un objectif, seule(s) la(les) variable(s) du système associée(s) à cet objectif va être modifiée de façon significative à long terme,
c. Toujours pour faciliter le pilotage, il est souhaitable que les objectifs répondent simplement vis à vis de la commande. On suppose donc que la variation de l'objectif est reliée à la variation de la commande pilote correspondante par une équation différentielle du premier ou du second ordre.

Bien entendu, ces quelques hypothèses ne sont pas suffisantes pour caractériser des modes supérieurs de pilotage. Il faut y ajouter des considérations de stabilité du système ou/et de satisfaction de critères de qualités de vol:

d. Puisque le nombre de commandes est inférieur à la dimension de l'état du système à contrôler, il n'est pas possible de piloter directement l'ensemble du système. Une partie de celui-ci dépendra directement du choix des modes supérieurs. Par définition, on appelle "ensemble des variables contrôlées", l'ensemble des variables associées aux objectifs de pilotage et "ensemble des variables non contrôlées", le sous espace complémentaire au précédent dans l'espace d'état [12].
e. Si la stabilité du système contrôlé est assurée, il faut encore s'assurer de celle du système non contrôlé.

7.1.2 Méthodologie de recensement des objectifs
Elle comporte les étapes suivantes:

a. choix des objectifs désirés,
b. calcul des modes non contrôlés,
c. si les modes non contrôlés sont stables, il ne reste plus qu'à régler la dynamique des modes contrôlés,
d. si les modes non contrôlés sont instables, il ne reste plus qu'à changer d'objectif (retour au point a).

Cette démarche fournit un premier choix permettant d'éliminer rapidement un grand nombre de modes indésirables. Le choix définitif des bons objectifs est effectué par les pilotes à l'issue des simulations pilotées.

7.2 Essais préliminaires à l'ONERA
Deux séries d'essais ont été réalisés à l'ONERA avec le concours de pilotes d'essais du CEV/Brétigny. La premières série a consisté en l'étude des lois longitudinales. La seconde série a été consacrée aux lois transversales et au comportement d'ensemble du système.

7.2.1 Modèle d'avion
Le modèle d'avion utilisé est le même que celui adopté dans le cadre des essais préliminaires de l'opération du GARTEUR (paragraphe 6.2.1). Outre le fait que ce modèle était déjà installé, il offrait surtout la possibilité de comparer les lois développées à l'ONERA et celles précédemment élaborées dans le cadre du GARTEUR.

7.2.2 Installation d'essais
Le poste de pilotage est sensiblement le même que pour les essais préliminaires du GARTEUR. A noter cependant que le mini-manche du NLR est remplacé par un autre mini-manche semblable réalisé à l'ONERA.

La symbologie tête haute est quasiment inchangée exceptée pour le losange qui indiquait la pente commandée et dont le déplacement demeurait dans le plan de symétrie de l'avion. Maintenant le losange indique les commandes longitudinales et transversales demandées et n'est donc plus astreint à se mouvoir uniquement de bas en haut et inversement dans le collimateur.

7.2.3 Conditions d'essais
Profitant des travaux du GARTEUR, et à des fins de comparaisons, les conditions d'essais retenues sont les mêmes que celles décrites au paragraphe 6.2.4.

Pendant la phase préliminaire de familiarisation avec les lois proposées et à l'issue de chaque essai, les pilotes sont invités à faire part de leurs remarques sur les lois proposées.

7.2.4 Lois de pilotage pour la première série d'essais
Cette première série d'essais est consacrée au mouvement longitudinal. Le mouvement transversal de l'appareil est contrôlé par la loi latérale adoptée pour l'opération GARTEUR.

A l'issue du recensement des modes longitudinaux, l'un des modes retenu est le pilotage de la vitesse (V) au moyen d'une auto-manette; quant à l'autre, il reste à faire un choix entre la vitesse de tangage (q), la pente de la trajectoire (γ) ou une combinaison de la vitesse de tangage, de l'incidence (α) et de la pente.

Trois lois longitudinales ont été retenues:

a. (V, q),
b. $(V, \gamma^{*}_{c} = \gamma + k_{1q}q)$,
c. $(V, \Gamma^{*} = \gamma + k_{\alpha}\alpha + k_{2q}q)$.

Pour les deux dernières, le pilote *commande* la vitesse de variation de γ^{*} et de Γ^{*}. De plus, pendant l'arrondi, les facteurs k sont modifiés en sorte de privilégier le contrôle de l'attitude.

7.2.5 Première série d'essais
En ce qui concerne la combinaison (V, q), l'opinion généralement exprimée est que cette loi est agréable à piloter, précise et très stable en turbulence. En revanche, les ordres au manche semblent trop fréquents par rapport aux lois "classiques".

Pour la loi (V, γ^{*}), la modification de la liaison entre l'ordre pilote et la commande effective de variation de pente rend cette loi agréable à piloter et peu sensible à la turbulence, aussi bien pendant le suivi du plan de descente que pendant l'arrondi. Le suivi de la trajectoire est plus précis et la charge de travail moindre qu'avec la loi (V, q).

Quant à la loi (V, Γ^{*}), son mauvais comportement en turbulence est très désagréable. Ce phénomène semble être caractéristique de cette loi et dû à l'introduction d'un terme d'incidence dans l'objectif.

A l'issue de ces essais, la loi (V, γ^{*}) a été retenue pour la poursuite de l'étude.

7.2.6 Lois de pilotage pour la deuxième série d'essais
Cette seconde série d'essais est consacrée surtout à l'étude des modes de pilotage transversaux.

A l'issue du recensement des modes transversaux, l'un des modes retenu est le pilotage du dérapage (palonnier); quant à l'autre, il reste à choisir entre la vitesse de roulis (p), la vitesse de variation du cap aérodynamique ($d\chi/dt$) ou la combinaison des deux.

Trois lois ont été retenues:

a. (β, p),
b. $(\beta, d\chi/dt)$,
c. $(\beta, p$ et $d\chi/dt)$.

La troisième loi est réalisée au moyen d'une commutation entre les deux premières suivant l'état de l'appareil et l'amplitude de l'ordre commandé. Lorsque l'ordre au manche est petit le pilote corrige finement le cap de l'avion (loi b). Lorsque l'ordre est grand, on suppose que le pilote désire mettre l'appareil en virage (loi a). Dans ce dernier cas, l'avion reste en virage quand le manche est ramené au neutre. A noter également que les lois b) et c) sont équipées d'un dispositif de maintien des ailes horizontales.

7.2.7 Deuxième série d'essais [13]
Pour les trois lois, le pilotage du dérapage a été jugé satisfaisant quoiqu'un peu lent. Le pilotage sans roulis (ou très faiblement) est apprécié pour la manoeuvre de "décrabage" près du sol.

Le pilotage roulis (loi a) ne permet pas d'effectuer aisément de petites corrections en finale. L'absence du retour ailes horizontales est ressenti comme une gêne par les pilotes.

Le pilotage en vitesse de variation du cap aérodynamique (loi b) est apprécié en approche finale car il permet d'obtenir une trajectoire précise, diminue la charge de travail et est peu sensible à la turbulence. Elle est agréable en approche mais un peu gênante en virage puisque le pilote doit maintenir un effort sur le manche.

La loi c), combinaison des lois a) et b) a été très appréciée des pilotes. Ils ont trouvé très satisfaisant de disposer d'une commande en roulis associée à la possibilité de faire facilement des petites corrections en approche finale malgré la persistance de quelques petits mouvements transitoires qu'il serait judicieux de faire disparaître.

Cette campagne de simulations pilotées a montré que les pilotes appréciaient les modes de pilotage par objectif. Il est également apparu très intéressant de les

combiner entre eux, suivant des règles à affiner, pour faciliter la tâche de pilotage. C'est essentiellement sur ce dernier point que porteront les essais au simulateur du CEV d'Istres.

7.3 Essais au CEV [14]
Devant l'intérêt des résultats obtenus au cours des simulations pilotées à l'Office, l'ONERA a souhaité implanter la meilleure loi sur le simulateur d'avion de transport du centre de simulation de CEV d'Istres afin d'accentuer le réalisme du pilotage et de recueillir les commentaires d'un plus grand nombre de pilotes.

7.3.1 Modèle d'avion
Le modèle utilisé est un AIRBUS A300B4 équipé de moteurs GE CF6-50 fourni au CEV et validé par l'AEROSPATIALE.

7.3.2 Lois de pilotage
Deux types de loi de pilotage ont été essayés à Istres. Le premier correspond à la loi ONERA. Le second correspond aux lois de pilotage réalisées par le CEV, en reprenant le principe de la commutation entre différents modes de pilotage dégagé à l'ONERA, à partir d'éléments de commande préexistants à Istres.

La loi ONERA a été implantée au centre de simulation après avoir été modifiée en sorte de prendre en compte le nouveau modèle d'avion. Elle est constituée des modes de pilotage suivants:

a. (V, $\gamma^* = \gamma + k_{1q}q$) pour le mouvement longitudinal,
b. (β, p et $d\chi/dt$) pour le mouvement transversal.

La loi du CEV comporte quatre variantes [14] qui se différencient par la façon de commuter d'un mode de pilotage sur l'autre. Indépendamment de cette commutation, ces lois sont fondées sur l'utilisation d'éléments de commandes de vol déjà implantées à Istres et validées par l'AEROSPATIALE. Il s'agit:

a. de la loi dite "C^*" de l'A320 constitué par le pilotage en facteur de charge pour le longitudinal et le pilotage en vitesse de roulis pour le latéral.
b. de la loi du pilote automatique avec le pilotage de la pente pour le longitudinal et le pilotage de la route pour le latéral.

La tenue de vitesse est faite par l'engagement de l'automanette.

7.3.3 Installation d'essais
La cabine de simulation est mobile (6 degrés de liberté) et accueille tous les essais relatifs aux avions de transport. Elle dispose de deux postes de pilotage:

a. en place droite, avec une planche de bord classique,
b. en place gauche, avec deux tubes cathodiques, un collimateur tête haute et un manche latéral type A320.

Le collimateur tête haute est inspiré de la symbologie du MIRAGE 2000. Outre les symboles habituels, en phase d'approche et d'atterrissage, il comporte les éléments suivants (figure 13):

a. une piste synthétique,
b. un repère de pente à -3 degrés,
c. la trace au sol de l'axe du LOC (localizer),
d. deux échelles d'écart LOC et GLIDE.

La visualisation synthétique de nuit permet de représenter la piste avec son balisage axial et latéral, la rampe d'approche, le VASIS et des repères lumineux indiquant le point d'impact à viser.

La cabine possède, en outre, un système complet de sonorisation AIRBUS A300.

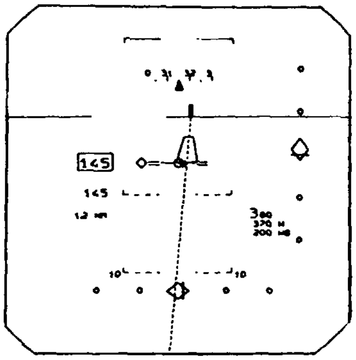


Figure 13 : Collimateur tête haute du CEV.

7.3.4 Conditions d'essais
Le pilote aux commandes est assis en place gauche. Les deux tubes cathodiques présentent une image PFD (Primary Flight Display) et une image ECAM (Electronic Centralized Aircraft Monitor).

Les conditions météorologiques sont variables à travers le choix de la visibilité horizontale et de la hauteur du plafond. Les conditions de vent et de turbulence peuvent être modifiées à tout instant.

7.3.5 Essais
Par rapport à l'ONERA, la mission à accomplir est beaucoup plus complète. Elle consiste en une approche ILS de l'aéroport de MARSEILLE-MARIGNANE pendant laquelle le pilote reproduit une manoeuvre d'évitement (en vertical et en latéral). D'autre part, afin de tester la maniabilité de l'appareil, le pilote ne fait pas un atterrissage classique, mais il doit réaliser une baïonnette à 500 pieds pour se poser sur une secondaire sans ILS.

Pour chaque loi de pilotage, il est demandé au pilote de fournir une appréciation de chacune des phases de vol (tenue de route/pente, évitement, virage, capture du LOC, descente sur le GLIDE, tenue de l'ILS et baïonnette à 500 pieds).

7.3.6 Résultats
Cinq pilotes ont participé à ces évaluations. La premières conclusion dégagée est que le principe de pilotage direct des paramètres pente/route/vitesse intéresse beaucoup les pilotes. Toutefois, il semble inacceptable de ne pas disposer également des possibilités de pilotage "manuel" classique.

En ce qui concerne la loi ONERA, elle a été appréciée dans les phases de vol pour laquelle elle avait été conçue. En revanche les pilotes ont éprouvé des difficultés pour réaliser les manoeuvres d'évitement, de baïonnette et de grandes variations de route, surtout en présence de vent et de turbulence pour le transversal. Sur ces différents points, il convient de noter que la loi ONERA ne traite pas les problèmes de l'évitement et du changement de la route. D'autre part, les paramètres pilotés sont des paramètres aérodynamiques et non des paramètres sol. Sur ce dernier point, l'utilisation des informations sol ou la mesure des perturbations atmosphériques comme dans la loi CEV serait de nature à régler définitivement le problème.

Quelque soit la version choisie, la loi CEV a été préférée par les pilotes pour deux raisons:

a. elle dispose d'une loi de pilotage par objectif,

b. le pilote peut revenir à tout instant en pilotage "manuel".

La seule critique concerne la maîtrise du passage entre les deux modes de pilotage et la symbologie.

En dépit des meilleures performances des lois CEV, élaborées à partir d'éléments de lois de commandes validées par le constructeur, la démarche poursuivie par l'ONERA a favorisé une réflexion de la part du CEV et des pilotes d'essais sur l'intérêt de la commutation aisée entre des modes de pilotage différents en vue d'améliorer la tâche de pilotage pendant la phase d'approche et d'atterrissage et, par extension, dans tout le domaine de vol.

A ce stade de l'étude, il conviendrait d'améliorer la loi de pilotage ONERA afin de répondre aux critiques des pilotes et de réfléchir à l'utilisation de son principe dans le cadre d'une étude prospective sur le pilotage des avions de transport futurs.

8. CONCLUSION

Le développement des applications de la technologie du contrôle actif augmente les performances des avions et réduit, entre autres, la charge de pilotage dans la mesure où il rend possible l'apparition de modes de pilotage nouveaux. Le gain apporté dans ce domaine ne peut pas être aisément quantifié et il est indispensable pour cela de faire intervenir le jugement de l'être humain.

L'introduction de l'être humain dès la conception de projets incluant de la commande automatique généralisée est en effet nécessaire pour analyser les aspects de qualité de vol, de confort, de pilotage et d'ergonomie associés aux concepts mis en oeuvre et, dans l'hypothèse de l'occurrence d'une "panne", pour vérifier que la dégradation du comportement de l'appareil n'est pas de nature à compromettre sa mission.

Depuis longtemps, a été perçue la nécessité de quantifier sur des bases objectives les qualités de vol des avions pilotés et il a été possible d'édicter des normes qui sont toujours en vigueur. Toutefois, ces dernières ne sont pas encore complètement adaptées à l'apparition de modes de pilotage non conventionnels ou/et à l'introduction de gouvernes nouvelles.

Ainsi, dès le stade de la conception d'un projet, l'utilisation de simulations pilotées reste donc un moyen d'investigation puissant pour étudier les différents aspects de l'utilisation de la technologie du contrôle actif dans les avions.

La communication a présenté trois exemples de concepts induits par la commande automatique généralisée pour lesquels les simulations pilotées sont apparues très tôt dans le déroulement des études:

a. un système intégré de commandes de vol et de conduite de tir canon Air-Sol pour lequel le pilote commande directement le point d'impact instantané des projectiles pendant la phase finale de l'attaque au travers de son mini-manche,
b. un concept de commandes de vol principales pour le vol longitudinal des futurs avions de transport en phase finale d'atterrissage; la commutation du système de commandes principales sur des lois de secours moins évoluées en cas de "panne" a également été examinée. Cette étude a été réalisée sous les auspices du GARTEUR en collaboration avec d'autres organismes de recherches (RAE, NLR, DLR),
c. un concept de commandes de vol complet (longitudinal et latéral) pour les mêmes avions que dans l'étude précitée.

Pour chaque exemple traité, deux moyens de simulation ont été successivement mis en oeuvre. Le premier est le simulateur de recherche de l'ONERA, le second est un simulateur à base mobile du CEV ou du NLR suivant l'exemple.

La synthèse des résultats dégagés au cours de ces trois études montre que ces installations sont tout à fait complémentaires. Le simulateur de recherche de l'ONERA est aisé à mettre en oeuvre, facile à reconfigurer et très utile au stade de la recherche amont sur de nouveaux concepts dont il convient d'explorer rapidement les diverses éventualités. Quant à la simulation pilotée au CEV ou au NLR, elle est beaucoup plus réaliste et crédible vis à vis d'utilisateurs potentiels. Cependant, il convient de noter que les résultats obtenus sur les simulateurs de vol (CEV, NLR) n'ont pas démenti ceux acquis sur le simulateur de recherche de l'ONERA mais, au contraire, les ont confirmés et affinés. De plus, grâce à une étroite collaboration, le mélange des équipes de conception et de simulation a été grandement profitable au déroulement et aux conclusions des études présentées. Ainsi, la complémentarité de ces deux moyens d'essais ne peut plus être mise en doute.

Dans l'avenir, face aux bouleversements entraînés par l'introduction de la commande automatique généralisée dans les avions, l'utilisation conjointe de moyens diversifiés de simulation pilotée semble être l'un des outils privilégiés à la disposition des concepteurs de systèmes "automatiques" pour explorer et valider les futurs concepts de commandes de vol, définir de nouvelles normes de qualités de vol adéquates et traiter les aspect ergonomiques associés.

9. REMERCIEMENTS

Cette communication rend compte d'études réalisées en partie à l'ONERA dans le cadre d'actions de recherche soutenues par la DRET (Direction des Recherches et Etudes Techniques), le STPA (Service Techniques des Programmes Aéronautiques) ou bien le GARTEUR (Group for Aeronautical Research and Technology in EURope).

Je voudrais remercier toutes les personnes, aussi bien à l'intérieur de l'ONERA qu'en dehors, qui ont contribué à la réalisation de ces études et celles qui m'ont aidé dans la réalisation de cette communication. Je voudrais rappeler notamment que le simulateur de l'ONERA a été mis en oeuvre par M[me] Michelon, que M[r] Dang a assuré l'essentiel de l'étude sur le tir air-sol, et que M[r] Costes m'a très largement aidé pour la mise en oeuvre de l'évaluation de la chaîne de pilotage pendant la phase d'approche. Enfin, qu'il me soit permis ici de remercier vivement la contribution du personnel des centres de simulations pilotées (NLR, CEV) et celle de tous les pilotes d'essais sans lesquels les évaluations n'auraient pas été aussi fructueuses.

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LE ROLE DE LA SIMULATION POUR L'ETUDE APIS

(Aide au Pilotage par Imagerie Synthétique)

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Resumé

Cet exposé présente les différents moyens de simulation mis *en œuvre* chez DASSAULT AVIATION pour l'étude APIS (Aide au Pilotage par Imagerie Synthétique). Le but de cette étude était de définir les concepts d'Interface Homme-Machine d'une imagerie synthétique calculée à partir *d'informations* embarquées et rafraichies en vol et permettant d'apporter au pilote une aide à la compréhension et à la décision quelles que soient les conditions de vol (basse altitude, mauvaise visibilité ...) et les conditions tactiques.

Ce document décrit :

- Les moyens utilisés pour produire des images statiques issues de l'analyse des besoins et permettant d'effectuer une première sélection des images satisfaisantes.
- L'utilisation de stations de travail pour générer et piloter en temps réel les solutions retenues et y apporter des améliorations *sur la représentation.*
- Le couplage des stations de travail à un calculateur temps réel et à *une cabine de simulation de type* RAFALE permettant le déroulement manuel ou automatique d'un suivi de trajectoire 3D dans un scénario simple et utilisé lors des évaluations par dix pilotes.
- Les *scénarios retenus* et les résultats obtenus suite à ces évaluations.
- Les suites et les retombées futures sur la définition des avions de combat DASSAULT.

Liste des abréviations

- APIS : Aide au Pilotage par Imagerie Synthétique
- AVI : Avionique
- CERMA : Centre d'Etudes et de Recherches de Médecine Aérospatiale
- CEV : Centre d'essais en vol
- CTH : Collimateur Tête Haute
- CTM : Collimateur Tête Moyenne
- DLMS : Digital Land Mapping System
- FLIR : Forward Looking InfraRed
- HUD : Head Up Display (cf CTH)
- IMC : Instrumental Meteorological Conditions
- OASIS : Outil d'Aide à la Spécification des Informations Système
- RVB : Rouge Vert Bleu
- STTE : Service Technique des Télécommunications et des Equipements aéronautiques
- TBA : Très Basse Altitude

1. INTRODUCTION

Dans le cadre du *développement exploratoire* APIS conduit par le STTE/AVI, DASSAULT AVIATION s'est vu confier un contrat pour une étude de 2 ans.

Le but de l'étude APIS est de présenter au pilote d'un avion de combat monoplace une imagerie synthétique à partir d'informations embarquées (altimétrie, planimétrie, menaces, plan de vol) et d'informations rafraichies en vol (menaces imprévues, changement de plan de vol). Cette imagerie doit permettre de faciliter la prise de décision dans différentes conditions météorologiques, conditions de vol (pénétration *basse altitude) et conditions tactiques.*

Dans ce contexte, on cherche surtout à procurer au pilote un moyen d'avoir une perception de l'environnement et de mieux comprendre ce que font les automatismes de pilotage et de gestion *de trajectoire.*

La mission choisie comme thème d'étude est la mission Air-Sol *en pénétration très basse altitude* avec veille Air-Air d'un avion de type RAFALE.

Les terminaux *envisagés pour ces visualisations* sont le collimateur tête haute et le collimateur tête moyenne.

Le concept APIS a pour origine *l'analyse des besoins* opérationnels en matière de représentation d'imagerie du monde extérieur.

L'étude porte sur la définition et le développement de telles imageries sur des moyens informatiques (au sol) et outils de type "simulateur d'étude".

Dans ce contexte le rôle de la simulation, en particulier celui du centre OASIS chargé d'aider à la conception et à la mise au point des interfaces Homme-Machine des avions DASSAULT, a été essentiel.

2. ANALYSE DES BESOINS

Durant la première *année d'étude, une place importante* a été accordée à l'analyse des besoins, en particulier pour les aspects pilotage et navigation, afin d'en dégager un concept de présentation des informations sur les différents supports de visualisations adoptés.

L'analyse des besoins a conduit aux axes d'études suivants :

- Visualisation tête haute:
  - Etude de la représentation du terrain (zone, discrétisation des données, présentation filaire et vidéo, élimination de parties cachées, référence de hauteur, distance, vitesse).
  - Etude des décalages de superposition au monde extérieur (dûs aux erreurs de localisation) et de leur influence sur la nature des présentations.
  - Critères ergonomiques (estompage de l'image, lissage).
  - Intégration de la symbologie de pilotage dans l'imagerie synthétique du monde extérieur.
  - Représentations ponctuelles d'obstacles.
  - Etude de la cadence de rafraichissement de l'image.
- Visualisation planche de bord (CTM) :
  - Type de représentation terrain (lissage, ombrage....).
  - Présentation tridimensionnelle (vue pilote ou vue de recul).
  - Représentation de la planimétrie (villes, fleuves, forêts...).
  - Champs et distance de représentation.
  - Représentation d'obstacles.
  - Représentation d'informations relatives à la trajectoire anticipée et à la trajectoire à suivre.

3. ETUDES ET PROPOSITIONS D'IMAGES STATIQUES

Suite à l'analyse des besoins, *le bureau d'études* a défini et mis en oeuvre des moyens matériels et a développé des logiciels afin de générer diverses images synthétiques statiques.

<u>Les moyens matériels</u> :

- Pour la génération des images : un calculateur IBM3090 et *des consoles graphiques intéractives ainsi qu'une station* graphique SILICON GRAPHICS IRIS 4D.
- Pour l'animation image par image : *un* magnétoscope et des cartes de pilotage.

<u>Les moyens logiciels</u> :

- La base de données géographiques GEOBASE multi-sources permettant de recevoir au minimum les fichiers DLMS ainsi que des enrichissements obtenus par numérisation *manuelle de carte IGN. Un extracteur* permettant de générer ces données géographiques (altimétrie et planimétrie) pour les simulations temps réel du centre OASIS.
- *Un ensemble logiciel écrit* en Fortran :
  - Permet de générer une image en perspective 3D en définissant son *point de vue, son contenu* et la représentation graphique des informations.
  - Permet de générer des vues 2D cartographiques.
  - Permet la génération d'images statiques, leur manipulation et archivage.
  - *Permet* la génération interactive des paramètres d'animation de scènes tridimensionnelles en images de synthèse et de les enregistrer image par image sur magnétoscope.

De nombreuses images *ont* été développées à l'aide de ces outils. Les travaux ont porté sur :

- Les images filaires 3D en étudiant particulièrement:
  - La définition de la zone visualisée,
  - la discrétisation du terrain,
  - *Le type de représentation* (carroyage, isodistance, fuyante, ligne de crête),
  - les techniques d'élimination de parties cachées,
  - L'implantation de trajectoire, d'obstacles,
  - La cadence de rafraîchissement.
- Les images 3D statiques pleines destinées à une *visualisation planche de bord présentées* sous divers
  - Vue du pilote : vue dont le point générateur est le même que *pour les images filaires tête haute.*
  - Vue Demi-Dieu : vue dont le point générateur est reculé puis rehaussé par rapport à l'avion.
  - Vue déportée : vue dont le point générateur est défini par une avance temporelle sur la mission effectuée par l'avion.

Un dossier des images étudiées a ainsi été réalisé et présenté aux Services Officiels. Une dizaine d'images a été retenue constituant ainsi une proposition de base pour les simulations temps réél prévues à OASIS. (voir figures 1, 2).

De plus, à partir des paramètres enregistrés lors d'un vol basse altitude sur MIRAGE 2000, des images statiques ont été réalisées puis animées en temps différé image par image. Ces images ont été créées avec les logiciels évoqués précédemment et ont fait l'objet d'une cassette vidéo. La comparaison directe, par présentation simultanée sur deux moniteurs de cette séquence avec les séquences de terrain synthétique, a permis de constater que la restitution des lointains dans l'image synthétique correspondait très bien à ce que l'on retirait de la vidéo du vol.

4. LE ROLE DE LA SIMULATION PILOTEE

Parallèlement à la définition des images statiques, un travail de préparation pour le développement des animations s'est déroulé au centre OASIS. Il a permis de définir l'architecture et les matériels à mettre en oeuvre ainsi que l'architecture logicielle retenue.

Durant la seconde année le rôle de la simulation pilotée dans l'étude APIS a été double :

1. *Au niveau de la conception/génération* et de la mise au point des images, la simulation a permis de proposer un grand éventail de solutions avec de nombreuses variantes pour chacune d'elles. Plusieurs séances de travail se sont tenues avec les Services officiels et des opérationnels devant des stations de travail, et ont permis par itérations successives de définir et de choisir des solutions basées *sur des critères de représentativité et même d'aller* au delà des idées initiales : représentation tête haute vidéo (HUD4), représentation des zones d'intervisibilité des menaces...
2. Au niveau des évaluations en *rejouant* fidèlement, pour divers pilotes n'ayant pas participé à la définition des images, les mêmes scénarios (garantie d'iso conditions). Les différentes solutions développées sur station de travail ont alors été couplées à une cabine RAFALE et ont permis de présenter simultanément les images CTH et CTM avec un monde extérieur cohérent (visuel de jour utilisant les mêmes bases de données terrain).

4.1 MOYENS MATERIELS

Le matériel utilisé pour les simulations APIS était *composé :*

- D'un calculateur ENCORE 97/80 pour la simulation du modèle avion, des asservissements à la trajectoire 3D et de la génération de la symbologie tête haute.
- D'un SILICON GRAPHICS pour la simulation de l'image synthétique tête haute.
- D'un SILICON GRAPHICS pour la simulation de l'image *synthétique tête moyenne.*
- D'un système SINTRA CONCEPT 80 pour l'affichage de la symbologie tête haute.
- De la cabine OASIS RAFALE D (voir figure 3) dans laquelle se déroulent, dans le cadre du programme RAFALE D, les études de définition d'interface Homme-Machine. Pour l'étude APIS nous avons utilisé en particulier le combiné CTH/CTM simulé, le manche, la manette.

L'organisation générale retenue pour l'architecture matérielle est présenté sur la figure 4.

4.2 LES DEVELOPPEMENTS LOGICIELS :

4.2.1 LES BASES DE DONNEES

L'élaboration des images APIS nécessite un certain nombre de données de natures différentes.

Les données "altimétriques" renseignent l'altitude du *terrain sur une zone* considérée.

La "planimétrie" rassemble des informations concernant des éléments présents de manière permanente sur le sol. Ces éléments peuvent être naturels (cours d'eau, ...) ou artificiels (villes, pylônes, ...), physiquement présents (routes, ...) ou imaginaires (frontières, ...).

Des informations d'aide au pilotage (essentiellement trajectoire de référence et menaces) sont également nécessaires.

FICHIERS ALTIMETRIQUES

Diverses contraintes telles que le temps de rafraichissement d'image et l'uniformité de présentation dans toutes les directions ont conduit à utiliser une représentation plane du terrain, découpé en carrés pour OASIS. Les fichiers altimétriques de référence pour l'étude APIS sont les fichiers DLMS fournis par le centre géographique inter-armées. Les fichiers exploités dans le cadre de la simulation à OASIS représentent une surface de 90 km x 90 km. Pour satisfaire les besoins exprimés ci-dessus, des traitements de projection et d'échantillonnage ont été effectués à partir des fichiers DLMS.

FICHIERS PLANIMETRIQUES

Parmi les nombreux éléments planimétriques disponibles et présentables au *pilote, ont été retenus pour l'étude les villes*, forêts importantes, fleuves de grande taille, lacs et obstacles dangereux.

Les critères d'importance relatifs aux éléments pré-cités sont de natures distinctes.

Les fichiers planimétriques de référence pour l'étude APIS sont les fichiers DLMS fournis par le centre géographique inter-armées.

Suite aux besoins exprimés plus haut, un certain nombre d'opérations a été nécessaire.

- Rassemblement des manuscrits correspondant à la zone *utilisée pour* APIS.
- Regroupement des lacs, villes, forêts et fleuves appartenant à plusieurs manuscrits.
- Recherche des éléments les plus importants. C'est ainsi que, suite aux critères de tri effectué pour la simulation, sur le terrain des évaluations (de 90 km de côté), étaient présents les 5 plus grandes forêts, les 8 plus gros cours d'eau ou lacs et les 9 plus grandes villes.
- Recherche des obstacles dont la hauteur dépasse les 2/3 de la hauteur de consigne.
- Projection de même type que pour l'altimétrie afin de se placer dans un repère cartésien.
- Recodage des éléments planimétriques dans de nouveaux *fichiers correspondant* aux besoins spécifiques d'APIS.

FICHIERS DE TRAJECTOIRE DE REFERENCE

La représentation d'une "trajectoire de référence" s'est rapidement révélée essentielle. La représentation retenue revêt la forme d'un ruban, plaqué au sol.

L'*élaboration et* la représentation de la trajectoire de référence dans l'image APIS nécessite la connaissance d'un fichier de points (x,y) régulièrement espacés, correspondant à la trajectoire 2D à faire figurer dans l'image. Les coordonnées doivent être exprimées dans le repère cartésien de l'altimétrie.

Le fichier de points peut avoir diverses origines. Il peut, par exemple, provenir de considérations lors de la préparation de mission, être renseigné en temps *réel* en fonction *du* déroulement de la mission, ...

Pour ce qui concerne la simulation, le fichier de points de trajectoire a été élaboré en temps différé ; en fonction d'une vitesse de vol *moyenne, de points de passage ou de routes* obligés, et de contraintes propres à l'avion (facteurs de charges maxi, ...), un algorithme a généré une trajectoire minimisant l'altitude moyenne.

Cette trajectoire donne, à pas régulier, les positions et attitudes de l'avion dans un repère cartésien identique aux repères d'altimétrie et de planimétrie utilisés.

Un second algorithme dit de "placage au sol" calcule les *intersections en* 2D *de* cette trajectoire avec les facettes du terrain.

Ce placage au *sol a pour rôle de "facettiser"* le *ruban de* la manière aussi fine que nécessaire pour qu'il se plaque parfaitement sur les facettes de terrain pré-existantes. L'ensemble des facettes élémentaires de trajectoire de référence est alors stocké dans un fichier spécial.

FICHIERS DE MENACES

La présentation des zones dangereuses a semblé judicieuse lors de l'étude.

De même que pour la trajectoire de référence, c'est la représentation sous forme de surface, collée au terrain qui a été retenue.

Ainsi, dans les visualisations CTM APIS, l'image de l'intervisibilité des menaces Sol-Air peut être plaquée au sol.

L'élaboration et la représentation de l'intervisibilité d'une menace dans l'image APIS nécessitent la connaissance d'un fichier de points (x,y) décrivant le contour 2D de l'intervisibilité de cette menace. Les coordonnées doivent être exprimées dans le repère cartésien de l'altimétrie.

Le fichier de points peut avoir diverses origines. Il doit, cependant, représenter une courbe fiable de l'intervisibilité de la menace. Il peut être calculé en temps *différé, ou renseigné* en temps réel en fonction des évolutions de l'avion.

Pour ce qui concerne la simulation, les fichiers de contour de domaine d'intervisibilité des menaces ont été élaborés en *temps différé ; après avoir "implanté"* des batteries *sol-air* de portée donnée dans le terrain, des calculs d'intervisibilité ont pu être effectués en fonction des positions géographiques et portée de chaque menace, et du relief du terrain environnant.

Dans un deuxième temps, ces fichiers de contour sont scrutés pour fabriquer des fichiers de facettes.
Ces derniers fichiers contiennent les facettes de terrain affectées par l'intervisibilité, et leur degré de risque.

Ces fichiers de facettes sont directement utilisés en simulation pour représenter les domaines d'intervisibilité en CTM.

4.2.2 LES IMAGES APIS SIMULEES:

Une dizaine d'images différentes ont fait l'objet de simulation temps réel sur des stations de travail SILICON GRAPHICS. Les logiciels étaient développés sous UNIX en *langage C et utilisaient la bibliothèque graphique* de SIlICON. Seules les images retenues par les Services Officiels pour les évaluations en cabine sont présentées dans ce document, elles sont référencées HUD1 - HUD4 et CTM2A/B.

DESCRIPTION ET ALGORITHME DES IMAGES TETE HAUTE

Le but de l'image synthétique APIS en HUD est de présenter, à l'échelle 1 car superposable au terrain réel, des informations de relief, trajectoires, obstacles à court terme (vol basse altitude avec assistance au pilotage). La symbologie *classique tête haute (réticules de navigation)* se superpose toujours à cette représentation 3D du terrain.

IMAGE HUD1

C'est une représentation synthétique monochrome filaire (vert). Le relief est figuré par des lignes iso-distantes les unes des autres, représentées sous forme d'arcs de cercles concentriques dont *l'avion est le centre*.

L'extraction de terrain est un "cône 2D" ayant pour sommet l'oeil du pilote et pour angle d'ouverture vers le monde extérieur, un angle issu des champs du viseur (champ vertical *et champ horizontal) et du roulis avion. L'arc de cercle fermant* ce cône, a pour valeur la distance maximale de présentation de terrain. A l'intérieur de ce cône, on effectue un balayage à iso-distance ainsi qu'un balayage à iso-gisement. Pour une iso-distance donnée, on joint chaque point d'intersection (x,y,z) par une ligne de couleur verte. *De plus, une loi d'atténuation* dépendant de la distance ligne visualisée /oeil pilote, permet d'estomper les isodistances proches évitant au pilote de se focaliser sur elles ; l'information essentielle dans le HUD se situent dans les distances moyennes.

Superposée aux lignes iso-distantes, la trajectoire de référence est représentée, plaquée au *relief* sous la forme d'un ruban noir bordé de chaque côté par une ligne verte.

Les obstacles sont symbolisés à leur emplacement réel. Seuls les obstacles dont la hauteur dépasse les 2/3 de la hauteur de consigne de vol, sont représentés.

Des arbres, aléatoirement disposés, peuvent enrichir cette image, en participant au rendu de l'impression de profondeur, de défilement.

Les menaces ne font pas l'objet de présentation dans les images HUD.

Une commande pilote baptisée "taux de terrain" permet d'alléger les visualisations *APIS* en fonction des conditions extérieures (météo, nuit, ...), la luminosité de la symbologie restant au maximum. Cette commande permet l'allégement total, la transition de *l'image HUD1 HUD4*, et de choisir *4 états* possibles de présentation du relief. Trois paramètres évoluent en sortie de cette commande, il s'agit de :

- L'espacement entre les lignes iso-distantes, ce qui donne plus ou moins de lignes présentées.
- La luminosité globale de l'image APIS (sauf trajectoire de référence).
- La distance maximale de présentation (information à plus ou moins long terme).

La figure 5 présente un exemple de HUD1.

La simulation pilotée a permis, grâce à de nombreux paramétrages, de définir les lois de *balayage en distance et* gisement, les lois d'atténuation du terrain et la loi taux de terrain.

SCHEMA DE CONSTRUCTION COMPLETE D'UNE IMAGE HUD1

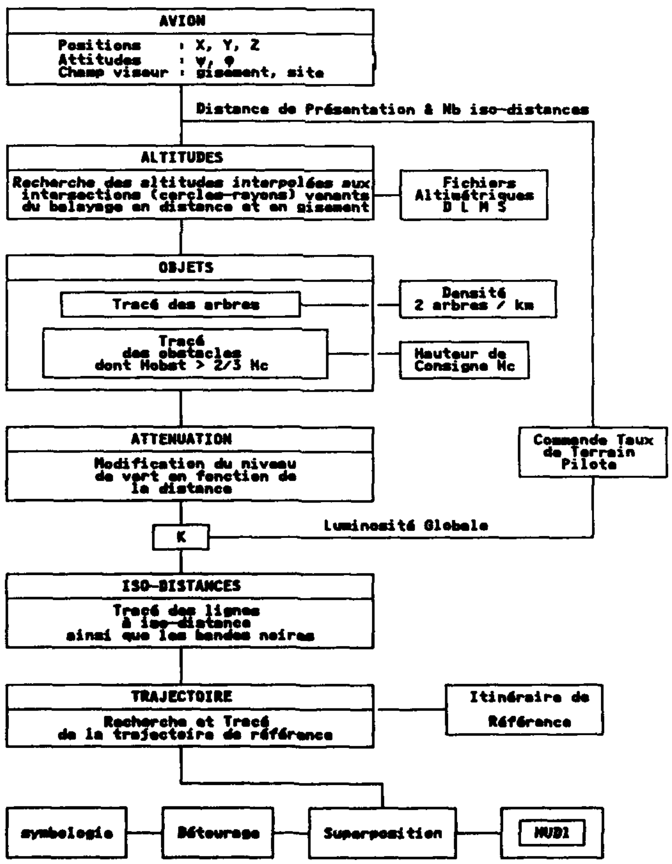


IMAGE HUD4

- Au cours de la mise au point de la simulation pilotée, il a semblé intéressant de présenter une image pleine plus facilement interprétable qu'une représentation filaire en cas de visibilité nulle ou de conditions météorologiques difficiles (IMC). Cette image est d'ailleurs plus naturelle et moins fatigante. La symbologie classique tête haute (réticules de navigation) se superpose toujours à cette représentation 3D du terrain.

C'est une représentation synthétique monochrome (vert) dite "Vidéo Pleine".

Le relief est figuré par une enveloppe épousant les différentes formes du terrain.

Superposée à cette enveloppe, la trajectoire de référence est plaquée au sol sous la forme d'un ruban noir.

Les obstacles sont symbolisés à leur emplacement réel.

Des arbres, aléatoirement disposés, peuvent enrichir cette image (idem HUD1).

La gestion des parties cachées est assurée pour l'ensemble de ces éléments.

L'extraction de terrain est définie par l'intersection des 4 lignes de visée (partant de l'œil pilote et passant par les 4 coins viseur) avec le terrain. A l'intérieur de cette zone, on effectue un balayage bidimensionnel respectant le maillage du terrain (fichier de données altimétriques). Suivant les 2 dimensions (Est et Nord), on cherche les informations d'altitude à intervalle régulier (maille du fichier altimétrique). L'élaboration de l'image nécessite la connaissance, pour chaque nœud du maillage, de la position géographique (altitude) et de la couleur choisie.

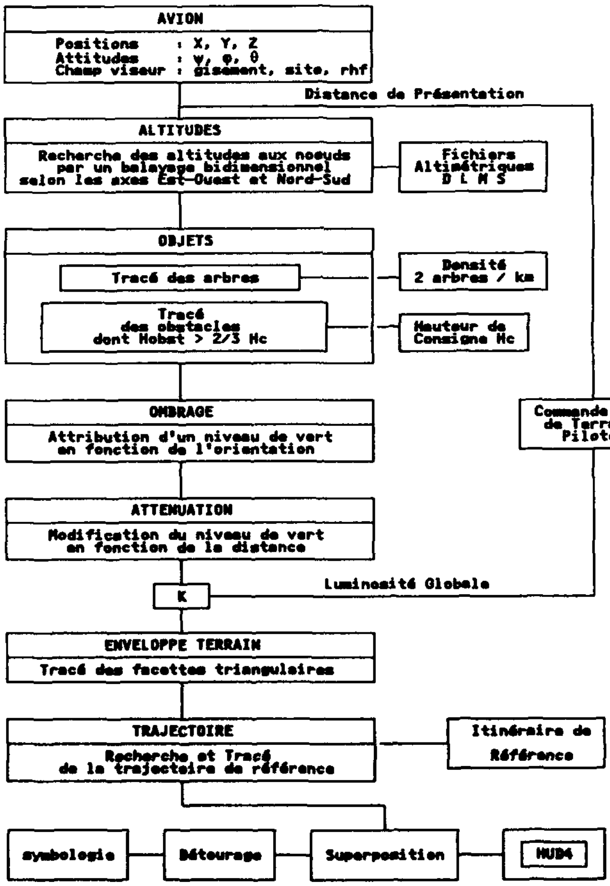
De plus, un algorithme de lissage est effectué sur l'ensemble de l'image.

La simulation pilotée a permis de définir la représentation HUD4 et particulièrement les lois d'atténuation.

La commande taux de terrain, telle que décrite pour HUD1, s'applique à HUD4 .

La figure 6 présente un exemple de HUD4.

SCHEMA DE CONSTRUCTION COMPLETE D'UNE IMAGE HUD4



nécessité de distinction : SYMBOLOGIE HUD / Images HUD APIS

A bord de l'avion, l'information essentielle de pilotage est la symbologie (réticules de navigation). Ceci signifie que l'image APIS est un plus par rapport à la symbologie et ne doit absolument pas dégrader sa lisibilité (puisque APIS est une "aide à la compréhension" de l'environnement, tandis que la symbologie reste l'information primaire de pilotage). Pour préserver cette priorité de présentation, les réticules possèdent une couleur vert saturé quelle que soit l'image APIS (HUD1 ou HUD4) présentée et quel que soit le "taux de terrain" affectant l'image APIS.

Afin d'accentuer la prédominance de la symbologie par rapport à l'image APIS, un détourage noir des réticules a été introduit. Cela permet une distinction nette de ces symboles et apporte une notion d'écriture en surimpression. Ceci est d'autant plus intéressant que l'image APIS est riche (beaucoup d'informations lumineuses en CTH), particulièrement pour l'image HUD4. La coexistence d'une symbologie et d'une image 3D APIS en tête haute a occasionné de légères modifications concernant la présentation de quelques réticules.

DESCRIPTION ET ALGORITHME DES IMAGES TETE MOYENNE

- L'image synthétique APIS en CTM permet d'obtenir une information moyen terme, dans le but de faire le lien visuel (donc d'analyse et de compréhension) entre l'image projetée dans le HUD (très court terme), et la cartographie (long terme).
- Cette image présente des informations de relief, trajectoire de référence, obstacles, menaces et planimétrie dans un champ très large (30° x 60°).
- Aucune symbologie classique ne se superpose à cette représentation 3D du terrain.

C'est une représentation synthétique monochrome (gris) afin de laisser toute latitude dans le choix des couleurs pour l'habillage.

L'image grand champ (60° x 30°) est issue d'un point d'observation situé en arrière et au dessus de son propre avion, n'évoluant ni en roulis (φ) ni en tangage (θ). Le relief est figuré par une enveloppe épousant les différentes formes du terrain. Superposée à cette enveloppe, la trajectoire de référence est plaquée au sol. Des zones d'intervisibilité de menaces, reflétant la possibilité d'être "accroché radar" par une batterie sol-air, sont représentées plaquées au sol. Des éléments planimétriques surfaciques tels que fleuves, lacs, forêts, villes sont symbolisés par autant de surfaces colorées épousant le relief. Les obstacles sont symbolisés à leur emplacement réel mais à une échelle supérieure à 1. La représentation de son propre avion se trouve toujours, pour l'observateur, dans le même site. Il évolue en φ, θ (roulis, tangage) contrairement à l'image et en ψ (cap) avec l'image. *La gestion des parties cachées est assurée pour l'ensemble de ces éléments.*

Diverses informations viennent compléter cette image :

- Informations de distance en NM représentées sous forme de lignes circulaires centrées sur l'avion.
- Information de hauteur du point d'observation.
- Information prédictive extrapolant la trajectoire de l'avion dans les 10 secondes à venir ("queue de scorpion").

L'extraction de terrain est définie par l'intersection des 4 lignes de visée (partant de l'œil observateur et passant par les 4 coins d'un objectif fictif d'ouverture 60° x 30°) avec le terrain. A l'intérieur de cette zone, on effectue un balayage bidimensionnel respectant le maillage du terrain (fichier de données altimétriques). Suivant les 2 dimensions (Est et Nord), on cherche les informations d'altitude à intervalle régulier (maille du fichier altimétrique).

La luminosité est calculée et elle dépend de :

- l'orientation locale du terrain (autour du nœud considéré) par rapport au soleil (pour le calcul d'ombre).
- la distance du nœud à l'œil du pilote (pour le calcul de l'atténuation).

La mer est représentée en bleu. La trajectoire est toujours représentée, même sur la mer.

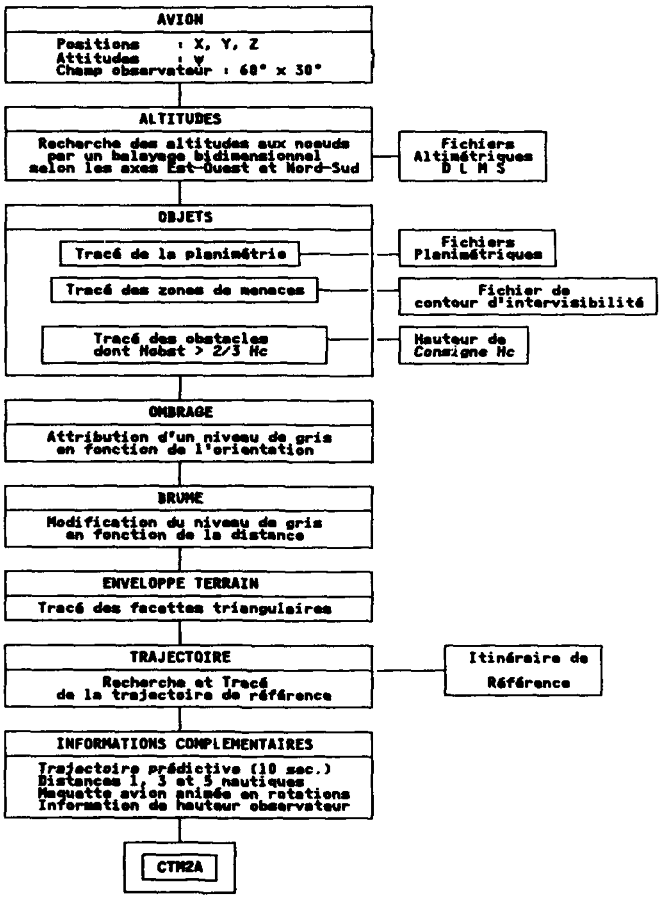
La simulation pilotée a permis la mise au point avec les opérationnels des caractéristiques de cette visualisation :

- position du point de vue,
- champ et distance de profondeur,
- représentation de la trajectoire,
- *représentation des menaces.*

De nombreux essais et de nombreux paramétrages ont été nécessaires pour aboutir à une image satisfaisante.

La figure 7 présente un exemple de CTM.

SCHEMA DE CONSTRUCTION COMPLETE D'UNE IMAGE CTM



5. LES EVALUATIONS

5.1 PRINCIPE DE L'EVALUATION PILOTEE

Le but de ces évaluations était de juger de l'apport d'imagerie synthétique au cours d'une mission très basse altitude dans différentes conditions météorologiques.

L'organisation de l'évaluation APIS en simulation pilotée à OASIS a été préparée et définie avec le CERMA, puis approuvée dans son principe par les Services Officiels, qui ont également désigné les pilotes évaluateurs.

La charge globale de travail demandée à chaque pilote était importante pour se familiariser aux commandes et à l'environnement de la cabine RAFALE-D et évaluer les différentes figurations et options APIS en CTH et CTM.

Ainsi chaque évaluation pilotée avait été scindée en 2 parties de 3 heures chacune (de préparation, puis d'évaluation) séparées de quelques jours d'assimilation.

La première séance comprenait :

- une présentation de l'étude APIS et des conditions d'évaluations.
- la présentation sur SILICON GRAPHICS de toutes les figurations (HUD1,HUD4,CTM2A/B) à évaluer ainsi que toutes les options possibles (arbres, obstacles, brume, taux de terrain ....).
- la présentation de la cabine RAFALE-D et des commandes.
- la simulation en mode TBA et en pilotage automatique avec possibilité de reprise en main sur 2 terrains (relief alpin élévé, relief moyen et mer).

La deuxième séance, véritable séance d'évaluation, d'une durée de trois heures pour chacun des pilotes s'est déroulée suivant des scénarios préétablis et identiques pour chaque pilote (scénario d'évaluation présenté en figure 8). Elle comprenait :

- le suivi de trajectoire TBA sur 3 terrains distincts,
- des informations planimétriques,
- des intervisibilités de menaces prévues et imprévues,
- des obstacles prévus et imprévus,
- des variations continues et cycliques des conditions de visibilité,
- des décalages simulant des erreurs de localisation ou de fichiers.

5.2 SYNTHESE DES AVIS DES EVALUATEURS

Un tableau de synthèse des jugements sur le rôle d'APIS, suite aux évaluations, est presenté figure 9.

APIS est unanimement considéré comme un progrès décisif dans la présentation d'information sur les avions de combat. Sa première qualité est de procurer un confort au pilote, contribuant à augmenter sa confiance générale dans ses possibilités de reprise en main du pilotage ainsi que dans son contrôle et sa compréhension du système d'arme en mode automatique, plus particulièrement en mauvaises conditions météorologiques.

L'option filaire isodistances tête haute (HUD1) a été globalement peu appréciée. Elle demande de façon générale un effort d'interprétation et est jugée moins informative que la représentation vidéo pleine HUD4 dans des conditions de mauvaises visibilité.

L'option vidéo pleine tête haute (HUD4) est appreciée par 9 pilotes sur les 10 et particulièrement en condition de mauvaise visibilité et en évolution sur terrain montagneux.

La représentation tête moyenne est jugée particulièrement bien réalisée techniquement, au point que peu de modifications seraient nécessaires pour l'embarquer sur un avion.

6. TRAVAUX ULTERIEURS

Suite à cette étude il est proposé :

- De transporter la simulation APIS au centre de simulation du CEV disposant d'un environnement plus réaliste afin d'affiner et de valider pleinement les concepts retenus.
- De préparer et d'assurer des essais en vol sur avion de servitude type MYSTERE 20 permettant d'embarquer une station SILICON GRAPHICS, afin de valider les concepts des images APIS dans des conditions basse altitude et mauvaise visibilité, ces conditions étant difficiles à réaliser en simulation en particulier au niveau du stress et de la charge de travail du pilote.
- Dans le cadre du programme RAFALE, un important travail de conception est en cours sur le TBA : usage de capteurs et fichiers, élaboration et suivi de la trajectoire, préparation de mission, superposition aux autres fonctions et bien sûr principes de présentation d'informations dans les visualisations.

Pour cela la capitalisation d'expériences résultant des travaux menés dans ces domaines, sur les programmes MIRAGE 2000 N et MIRAGE 2000 D mais aussi dans le cadre de l'étude APIS, constitue un apport fondamental.

7. CONCLUSION

La simulation aura permis d'affiner un concept, de juger de sa pertinence et de son applicabilité avant tout développement matériel et logiciel embarqué, contribuant de cette facon à la maîtrise des coûts de développement.

FIGURE 1 : Proposition image HUD

FIGURE 2 : Proposition image CTM

FIGURE 3 : Cabine de simulation

FIGURE 4 : Architecture Matérielle de la Simulation Pilotée

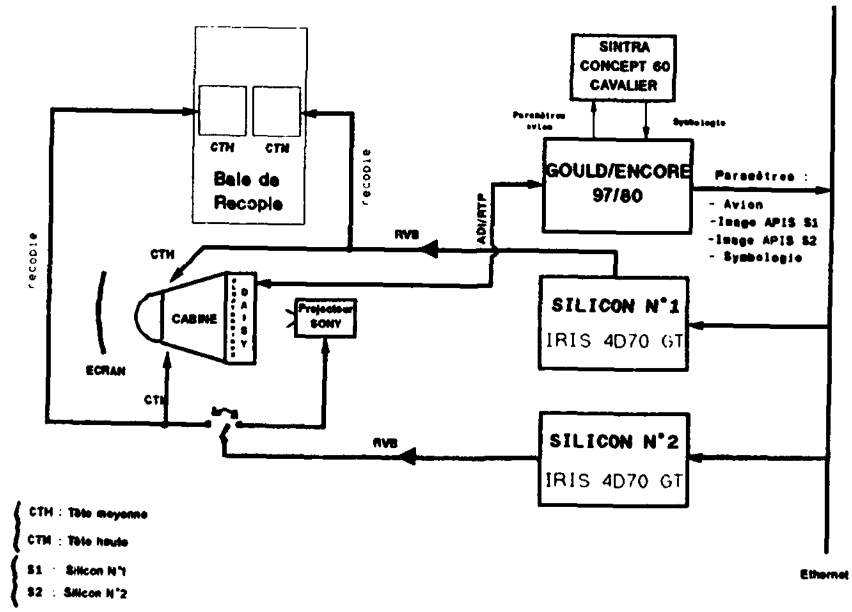


FIGURE 5 : Image HUD1

FIGURE 6 : Image HUD4

FIGURE 7 : Image CTM

FIGURE 8 : Exemple de Scènario

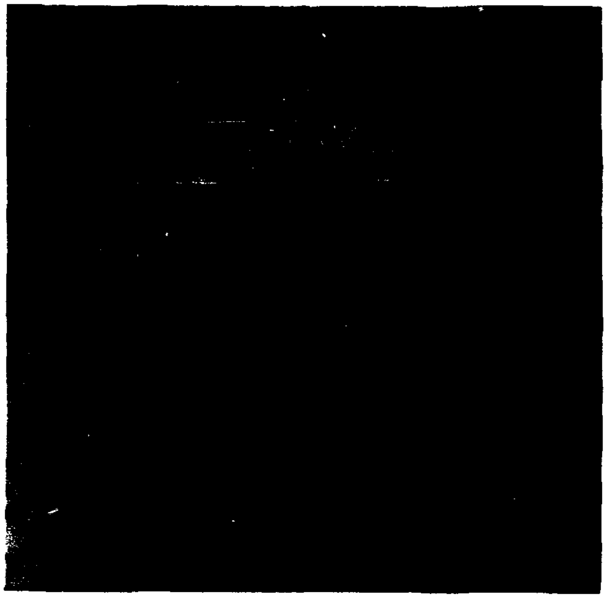


FIGURE 9 : Synthèse des Evaluations

En CTH :

	Rôle essentiel	Utile	Sans intérêt
Compréhension de la situation instantanée	10		
Anticipation des actions pilote automatique	5	3	2
Pilotage manuel	1	5	4
Compréhension de la situation tactique			10

En CTM :

	Rôle essentiel	Utile	Sans intérêt
Compréhension de la situation court-moyen terme	5	5	
Anticipation des actions pilote automatique	2	4	4
Pilotage manuel	3	3	4
Compréhension de la situation tactique	5	5	

THE USE OF GROUND BASED SIMULATION FOR HANDLING QUALITIES RESEARCH: A NEW ASSESSMENT

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ABSTRACT

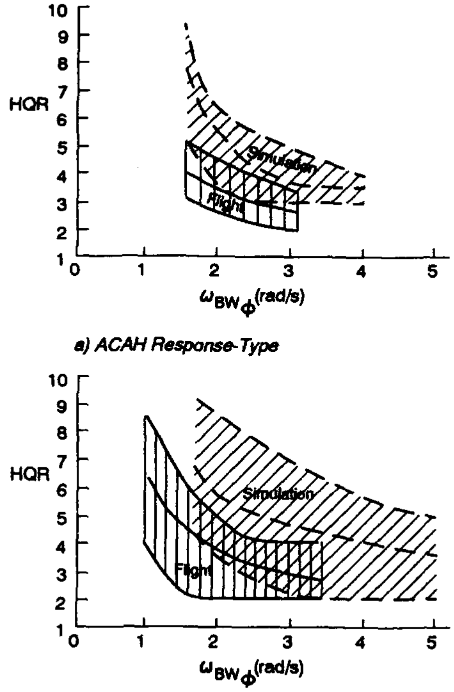
The pilot's perceptions of aircraft handling qualities are influenced by a combination of the aircraft dynamics, the task, and the environment under which the evaluation is performed. When the evaluation is performed in a ground-based simulator, the characteristics of the simulation facility also come into play. A study was conducted on NASA Ames Research Center's Vertical Motion Simulator to determine the effects of simulator characteristics on perceived handling qualities. Most evaluations were conducted with a baseline set of rotorcraft dynamics, using a simple transfer-function model of an uncoupled helicopter, under different conditions of visual and overall time delays with three sets of motion command washout filters. Differences in pilot opinion were found as the visual and motion parameters were changed, reflecting a change in the pilots' perceptions of handling qualities, rather than changes in the aircraft model itself. The results indicate a need for tailoring the motion washout dynamics to suit the task, with reduced washouts for precision maneuvering as compared to aggressive maneuvering. Visual-delay data are inconclusive but suggest that it may be better to allow some time delay in the visual path to minimize the mismatch between visual and motion, rather than eliminate the visual delay entirely through lead compensation. The simulation results are compared with ratings from a similar in-flight simulation experiment.

INTRODUCTION

Ground-based simulation is an important tool in the assessment of handling qualities for both research and development. The strengths and limitations of simulation are well known and recognized in the handling qualities community. What is not as well documented, however, is the relative impact of various elements in the simulator itself on perceived handling qualities. For example, past studies have demonstrated that rate-augmented vehicles that exhibit good handling qualities in flight are much more difficult to control on ground-based simulators[1] (e.g., Fig. 1).

Besides the obvious issues of simulation fidelity and flight/simulation transference,[2] there are other fundamental issues in simulation design that also impact the use of ground-based simulators for handling qualities research. All of these issues, such as inherent time delays and their compensation,[3,4] simulator sickness,[5] and the requirements on motion,[6-9] have been investigated in great detail in terms of their impact on human operator response dynamics and assessments of fidelity. Few studies, however, have explored the specific impact of these issues on handling qualities evaluations.

A study was conducted on NASA Ames Research Center's Vertical Motion Simulator (VMS) to evaluate the effects of simulator characteristics on handling qualities. The primary focus of the simulation was on



a) ACAH Response-Type

b) RCAH Response-Type

Figure 1. Comparison of Handling Qualities Ratings Ranges from Simulation and Flight for Landing[1]

piloted assessment of the variations — i.e., Handling Qualities Ratings (HQRs) and comments. Most evaluations were conducted with a baseline set of vehicle dynamics, using a simple transfer-function model of an uncoupled helicopter with Level 1 handling qualities based on Aeronautical Design Standard ADS-33C[10]. Changes in the simulation environment were made by adding time delays in the visual path and in the overall simulated response, and by changing motion system washout filter dynamics. The pilots were instructed to evaluate each variation in the environment as if it were a new aircraft; therefore, it may be assumed that differences in HQRs were due entirely to the pilots' perceptions of handling qualities, rather than to changes in the aircraft model itself.

FACILITY

Hardware

The VMS is a six-degree-of-freedom simulator with a cab mounted on a Rotorcraft Simulator Motion Generator (RSMG) gimbal (Fig. 2). Translational motion is limited by hard stops at ± 30 ft vertically, ± 20 ft laterally, and ± 4 ft longitudinally. Software trips in the motion system further limited the available range of linear travel from center position to ± 25 ft vertically, ± 18 ft laterally, and ± 2.5 ft longitudinally. The cockpit was representative of a single-pilot helicopter configuration with three horizon-level monitors for the out-the-window view; the rightmost window included a view of the ground environment near the helicopter as well. Visual display generation was via a Singer-Link Digital Image Generator (DIG I). Conventional cockpit head-down instruments were used, with the addition of a digital altimeter. No head-up displays were used. Cockpit controls were conventional, with a center-mounted cyclic, left-hand collective, and pedals. The command signals were displacement for all controllers. Cyclic stick characteristics were symmetric for pitch and roll. Force/deflection dynamics of the cyclic were estimated to be approximately

$$\frac{F_s}{\delta_s} = \frac{11.4^2}{s^2 + 2(0.3)(11.4)s + 11.4^2} \left[\frac{\text{lb}}{\text{in.}}\right]$$

in both pitch and roll.

VMS NOMINAL OPERATIONAL MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±30	16	24
LATERAL	±20	8	16
LONGITUDINAL	±4	4	10
ROLL	±18	40	115
PITCH	±18	40	115
YAW	±24	46	115
ALL NUMBERS, UNITS ft, deg, sec			

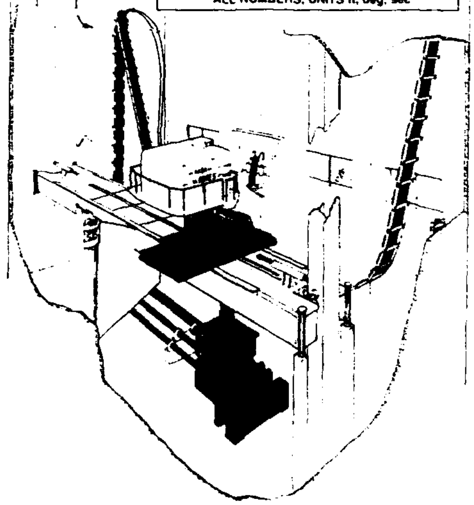


Figure 2. Vertical Motion Simulator

Timing Diagrams

Figure 3 is a schematic of the simulation layout. Cockpit control deflections, $\delta(s)$, are sampled by an analog-to-digital (A/D) converter and sent via digital to-digital (D/D) interface to the host computer (point A on Fig. 3). The host computer for the simulation model was a CDC 7600 operating at a cycle rate, T, of 50 samples per second (20 ms frame time). Model accelerations, w(z), are computed at every sample (point B). The model accelerations are used by the motion-drive software to compute motion drive command signals, $w_d(z)$ (point C). These signals are sent via D/D and D/A to the cab motion system. Sampling of the responses of the VMS motion system accelerations, $w_m(s)$, and rates, $v_m(s)$, requires an additional A/D and D/D interface (point D).

Model rates, u(z), are computed from the model accelerations with an advancing-integration algorithm that effectively provides a one-cycle lead (point F on Fig. 3). Model positions, u(z), are then integrated from the rates (point G) to compute the computer-generated imagery (CGI) commands for the DIG. A visual delay compensation algorithm[3] is used in simulations on the VMS to provide lead adjustment to offset these transport delays. Evaluations were made with this compensation algorithm both on and off. The CGI position commands, $u_c(z)$ (point H in Fig. 3), are transmitted via a D/D interface to the cockpit visual display. The DIG computer operated at 30 samples per second (33.3 msec frame time). The DIG computer uses a pipeline that requires a total of 2-1/2 computer cycles to generate an image and fill half of the monitors in the cockpit, resulting in an effective time delay of (2.5)*(33.3) = 83.3ms.

Time Delays

Linear accelerations and angular rates of the cockpit were measured during the simulation using both standard equipment and an add-on package of accelerometers and rate gyros. Frequency responses of the cab were obtained, from which estimates of the effective motion time delays were made. Confirmation of all time delays in the simulation, including documentation of the inherent delays in the model and motion elements, was performed at the start of the simulation. Timing diagrams generated by NASA personnel isolated phantom delays such as "recording delays" from those delays actually in the simulation.

Figure 3 shows the sources of time delays in the VMS facility. The delays due to the A/D and D/D (T_{AD} + T_{DD}) interfaces total about 10 ms. The model acceleration was subject to a one-cycle delay of the computer, T = 20 ms. Lead compensation in the

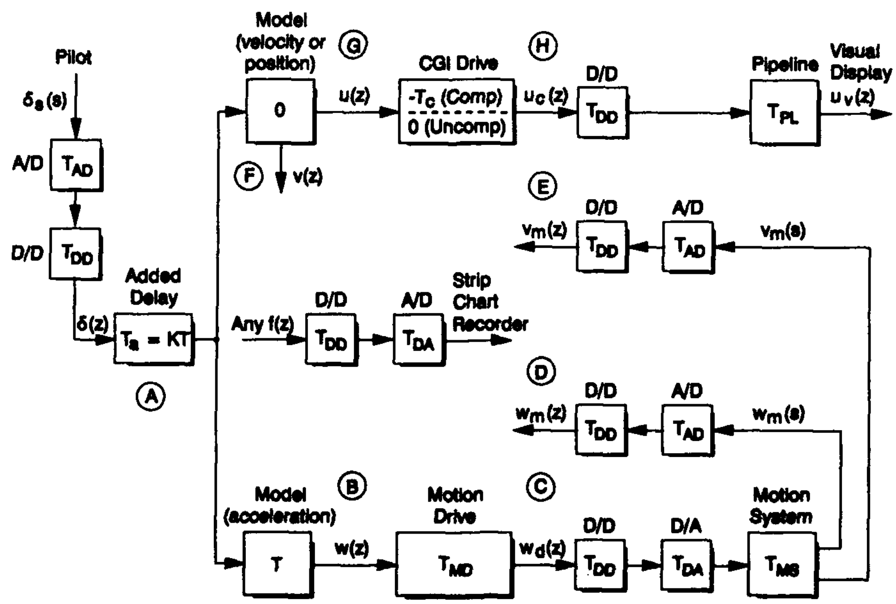


Figure 3. Delay Sources in the VMS Simulation Facility

motion drive algorithms effectively removed this one-cycle delay for commands to the motion system (i.e., $T_{MD} = -T$). Motion system delays, T_{MS}, were measured from frequency responses. The VMS motion system frequency response may be characterized in any axis as a cascaded combination of a second-order lag plus time delay; for the purposes of this experiment, however, this lag-plus-delay combination may be approximated sufficiently by a pure time delay, τ_m. The estimated values of τ_m for the VMS were 70 ms for pitch and roll angular velocities; 110 ms for yaw angular velocity; and 170 ms for longitudinal (surge), 100 ms for lateral (sway), and 160 ms for vertical (heave) linear accelerations. The total throughput delay for motion response to cockpit control inputs is, therefore (Fig. 3), $2(T_{AD} + T_{DD}) + \tau_m$, resulting in 90 ms in effective delay for the pitch and roll responses.

For the visual path in Fig. 3, the advancing integration from acceleration to velocity removes the delay due to computer cycle time, resulting in no net delay. The compensation filter in the CGI drive produces an effective time lead of 83.3 ms ($-T_c$) when it is active, and 0 ms when it is not. The D/D delay $T_{DD} = 2$ ms and is negligible. Finally, pipeline delay T_{PL} is 83.3 ms. The total delay in the cockpit visual response to cockpit control inputs is, therefore, $T_{AD} + T_{DD} - T_c + T_{PL} = 10$ ms (compensation on) or 93.3 ms (compensation off).

Motion Washouts

The VMS employs linear, constant-coefficient motion washouts referenced to both angular and linear accelerations. The washouts consist of second-order filters of the following form:

$$\frac{\text{simulated acceleration}}{\text{model acceleration}} = \frac{K_{wo}\, s^2}{[s^2 + 2\zeta_{wo}\omega_{wo}s + \omega_{wo}^2]}$$

Two sets of motion washouts were devised and evaluated in the experiment. These washout filter sets were designed to transmit different forms of acceleration information to the pilots. Details of the two washout filter sets are given in the next section of this paper. As a comparison, several evaluations were also performed fixed-base.

DESCRIPTION OF THE EXPERIMENT

Effects of variations in the three major elements of the simulation — the motion and visual systems and math model — were evaluated. In this paper only the first two elements are discussed. Specific variations and the philosophies behind them were as follows.

Motion System

Even though the VMS provides a large range of linear and angular travels, there are still very tight limitations on maneuvering space that necessitate lowered response gains and high washout break frequencies.[9] The selection of such gains and washouts is a compromise between the desire for realism in motion and the realities of space limitations. Potential criteria for determining washout limits (both gain and break frequency) for linear washouts have been developed.[11,12] These limits generally indicate that for minimum loss of motion fidelity, washout filter break frequencies should be no greater than about 0.3 rad/s (for a second-order filter with damping ratio of 0.7). Ideally, the values selected reflect the requirements of the particular maneuvers to be flown and the expectations of the pilot. For a thorough treatment on the demands and desires for motion system responses, it is useful to consider the capabilities of the human to sense motion in the first place.

Human Perceptions of Motion. Human perceptions of motion stimuli are quite complex and are best handled in volumes on sensory perception.[13] The interest here is on a very narrow subset of perception, limited to transfer-function representations of motion perception around the frequencies of interest for most compensatory and pursuit operation.[14] The sensation of motion in humans is provided by a combination of vestibular and kinesthetic cues. Thorough transfer-function models of the vestibular system have been developed;[6,15] the distributed nature of the kinesthetic receptors, located throughout the body in muscles, skin reactions, tendons, etc., makes such representation difficult. The vestibular system, located in the temporal bones in the head, consist of the semicircular canals and the utricles. The semicircular canals are responsive to angular accelerations, but their dynamic characteristics are such that over the range of frequencies normally used in manual control they may be considered as rate gyros to provide the human with a subjective impression of angular velocity. Figure 4a shows a model for the semicircular canal path. The utricles are linear accelerometers that respond to applied specific force. A model for the utricular path is shown in Fig. 3b.

Baseline Washout Dynamics. The Baseline set of motion washouts used in this experiment was developed for the simulation by NASA engineers. This Baseline set followed the NASA philosophy of transmitting initial accelerations at the expense of motion/visual/model phasing.[9] Scaling on the initial response was on the order of 30% to 60% of full scale, with washout break frequencies of 0.2 to 0.7 rad/s. The washout filters selected are defined in Table 1, and an example frequency response is shown in Fig. 5. This figure compares the washout filter characteristics

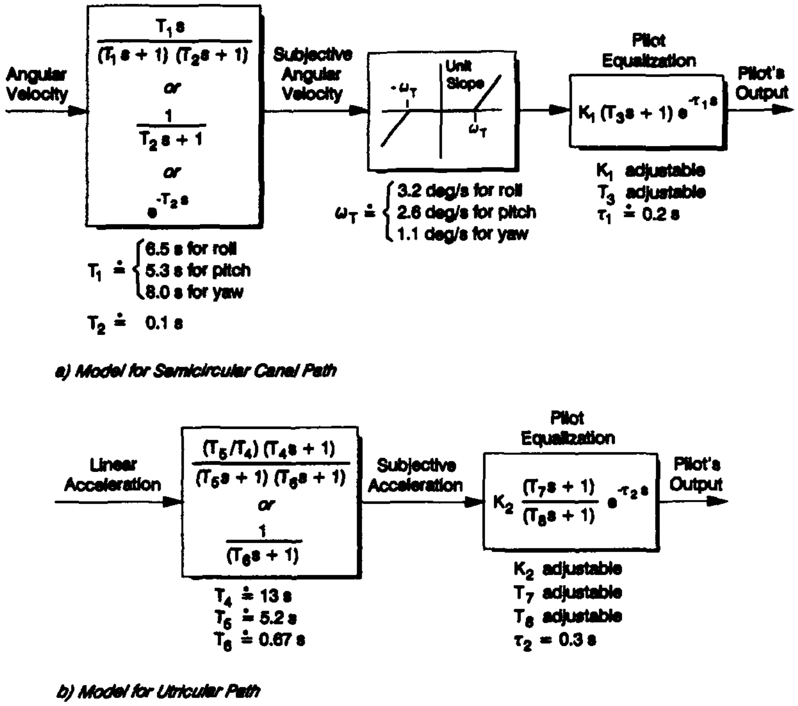


Figure 4. Simple Models for the Vestibular System[6]

TABLE 1. MOTION WASHOUT FILTERS

AXIS	BASELINE SET	MODIFIED SET
Roll	$\frac{0.3(0)^2}{[0.707,0.7]}$	$\frac{0.15(0)^2}{[0.707,0.3]}$
Pitch	$\frac{0.5(0)^2}{[2.0,0.2]} = \frac{0.5(0)^2}{(0.054)(0.746)}$	$\frac{0.25(0)^2}{[0.707,0.3]}$
Yaw	$\frac{0.3(0)^2}{[2.5,0.2]} = \frac{0.3(0)^2}{(0.042)(0.958)}$	$\frac{0.3(0)^2}{[2.5,0.2]} = \frac{0.3(0)^2}{(0.042)(0.958)}$
Surge	0	0
Sway	$\frac{0.8(0)^2}{[0.707,0.6]}$	$\frac{0.6(0)^2}{[0.707,0.6]}$
Heave	$\frac{0.6(0)^2}{[0.707,0.3]}$	$\frac{0.4(0)^2}{[0.707,0.05]}$

NOTES: a) Shorthand notation is $(a) \equiv (s + a)$, $[\zeta,\omega_n] \equiv [s^2 + 2\zeta\omega_n s + \omega_n^2]$

b) Filters are for $\frac{\text{simulation acceleration}}{\text{aircraft acceleration}}$

c) Values are for low speeds (below 20 kt)

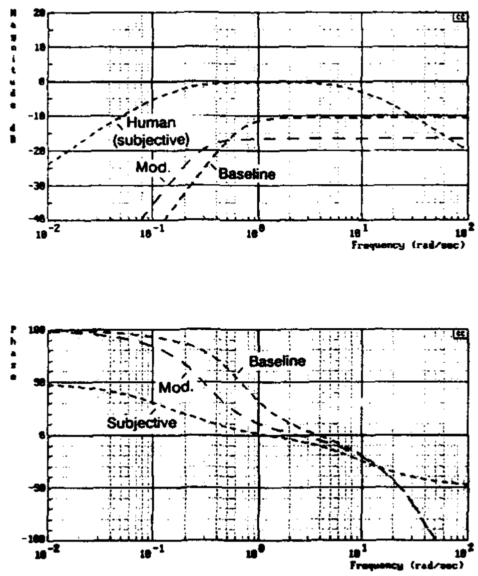


Figure 5. Comparison of Roll Rate Frequency Response Characteristics of Human Vestibular System (Subjective/Actual Angular Velocity) with Motion Washout Filters(Washout Filters Include VMS Response Delay of 70ms)

(with the effective time delays of the VMS motion drive added) of the Baseline system with the pilot's subjective semicircular canal response to a roll rate input. The response of the semicircular canals is effectively a first-order washout at low frequencies and a lag at high frequencies. The Baseline motion washout introduces a substantial reduction in amplitude at low to mid frequencies (approximately 0.2 to 1 rad/s) and a significant phase difference up to about 2 rad/s.

Modified Washout Dynamics. An alternate set of Modified washouts was developed during the simulation. This set was designed with the specific goal of reducing the phase distortions in motion around the frequencies of pilot closed-loop control (and maximum acceleration sensitivity), 0.5-5 rad/s. Since this requires a washout break frequency below that of the Baseline washouts, the decreased phase distortion comes at the expense of further attenuated amplitude of motion. The filter dynamics of the Modified washouts are included in Table 1, and an example is included in Fig. 4. The Modified roll washout attenuates amplitude at all frequencies but with much less phase distortion, resulting in reasonable correspondence with the subjective response at frequencies above 0.6 rad/s.

Visual System Delays

While the visual compensation filter[3] used on simulations on the VMS effectively removes the overall visual delays, it increases the mismatch in phasing between the visual and motion responses: the motion system experiences unavoidable delays due to mass, inertia, and control limiting effects that cannot be removed entirely. Past studies of time delays in either the visual or motion path, resulting in a visual/motion mismatch, show mixed results. For example, a simulation on the NASA Ames Six-Degree-of-Freedom (S.01) simulator[16] suggests that based upon measures of pilot performance, 1) it is better to have the motion response lag visual rather than to intentionally lag the visual just to reduce mismatch, and 2) in terms of pilot high-frequency lead generation, motion compensation is more important than visual compensation. A study of a vertical pursuit tracking task on the NASA Langley Visual/Motion Simulator[17] investigated visual/motion mismatch by introducing delays in the visual system. Pilot performance measures of total tracking error and control activity were taken. Slight improvements in performance were found for the case where total visual delay most closely matched the effective delays of the motion system (approximately 97 ms).

Effects of removing the visual delay compensation were evaluated and compared to adding an equivalent pure time delay in the overall simulation.

MATH MODEL

The mathematical model for the rotorcraft was a generic, uncoupled stability-derivative model that has been used for several simulations at Ames.[18] Changes in dynamic response characteristics are effected by altering the basic aircraft stability and control derivatives; for example, the transfer function for pitch attitude response to longitudinal cyclic for the baseline Rate Response-Type was represented by

$$\frac{\theta}{\delta_e} = \frac{M_{\delta_e}}{s^2 - M_q s}$$

The baseline Rate Response-Type had $M_q = L_p = -4$ rad/s and $M_{\delta_e} = L_{\delta_a} = 1.4$ rad/s²/in. Heave and yaw dynamics were fixed throughout the simulation at values that exceeded the Level 1 requirements of ADS-33C.

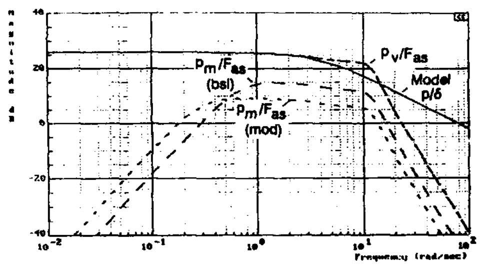
CHARACTERIZATION OF THE DYNAMICS

The dynamics of the tested configurations were characterized in terms of their pitch and roll attitude Bandwidth parameters,[10] i.e., Bandwidth frequency ω_{BW} and phase delay τ_p. Each of the time-delay

sources in the VMS facility outlined in Fig. 3 can have a very large effect on the values of these parameters. For ground-based simulation, it is necessary to properly account for three separate response elements, the math model, the visual scene, and the motion system, since the pilot is, to some extent, aware of and operating in response to all of them. In the case of the VMS it is possible for the Bandwidths of these three responses to be quite different for the same configuration. An example of this is shown in Figs. 6 and 7.

The frequency-response plot of Fig. 6 illustrates the dramatic effects of cascading the individual elements of the simulation onto the ideal math model. The model (shown as solid lines in Fig. 6) is the baseline Rate system; p/δ represents the model response to measured control position (i.e., after the A/D and D/D interfaces in Fig. 3). As expected, in the absence of time delays this ideal system exhibits a Bandwidth frequency of $\omega_{BW_\phi} = -L_p = 4$ rad/s, and phase delay $\tau_{p_\phi} = 0$.

The response of the compensated visual display (p_v/F_{as}) in Fig. 6 is referenced to cockpit control force



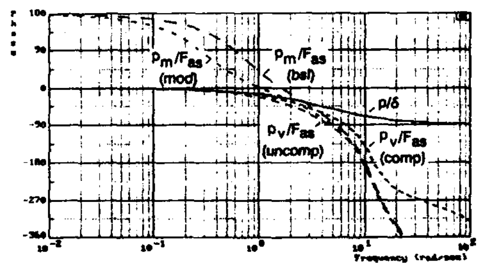


Figure 6. Frequency-Response Comparisons of Roll Rate to Control Input (Inputs are Measured Control Position, δ, and Cockpit Control Force, F_{as}; Outputs are Roll Rate for Model, p, Visual Display, p_v and Motion p_m)

inputs, thereby introducing two delay-inducing elements at once: the 10-ms measurement delay for the A/D and D/D (Fig. 3), and the second-order lag at 11.4 rad/s resulting from the feel system filtering. The feel system has the most profound effect on this response; Bandwidth frequency is reduced from 4 rad/s to 2.77 rad/s, and phase delay increased from 0 s to 0.142 s. Turning the visual compensation filter off does not affect the magnitude curve (since we are assuming this filter is effectively a pure time delay), but there is further phase lag, with $\omega_{BW_\phi} = 2.07$ rad/s and $\tau_{p_\phi} = 0.151$ s.

The actual response of the VMS cab (p_m/F_{as} in Fig. 6) is quite different from the model and visual responses. The combination of washout filter (from Table 1) and effective time delay of 90 ms contributes low-frequency phase lead and high-frequency phase lag. The low-frequency lead introduced by the motion washouts serves to increase the Bandwidth frequencies, with $\omega_{BW_\phi} = 3.11$ rad/s for the Baseline washout and 2.58 rad/s for the Modified, but the motion-system lags increase phase delay to $\tau_{p_\phi} = 0.176$ s and 0.163 s, respectively.

Figure 6 serves to illustrate several important points. First, it shows the significant effect of the cockpit force-feel dynamics. Second, it shows the beneficial effect of the visual compensation filter, since the phase curve of the compensated response is closer to ideal to higher frequencies (until the stick feel system dynamics swamp the response). Third, the phase distortions and gain reductions introduced by both the Baseline and Modified washouts are evident, as the responses of the ideal math model and cab roll motion are in phase for effectively only a single frequency. In addition, Fig. 6 shows that in terms of visual-motion synchronization, the uncompensated visual response actually corresponds most closely to the motion response, especially at high frequencies.

The significance of the Bandwidth differences of Fig. 6 is illustrated by Fig. 7. This figure shows the ten possible measurements of the Bandwidth parameters to describe the responses of Fig. 6. The parameters for the ideal model are the most straightforward, especially for position-referenced values of measured roll rate to measured stick deflection (p/δ). The visual-display Bandwidth, with compensation on, is referenced back to cockpit control inputs, ϕ_v/δ_{as}, and hence reflects 10 ms of time delay; with compensation removed the Bandwidth drops to about 2.5 rad/s and phase delay increases to 0.07 s. The phase delays for motion are about equal to those for the uncompensated visual display, but with increased Bandwidths due to the washouts. Addition of the stick force feel dynamics greatly increases τ_{p_ϕ} and decreases ω_{BW_ϕ}.

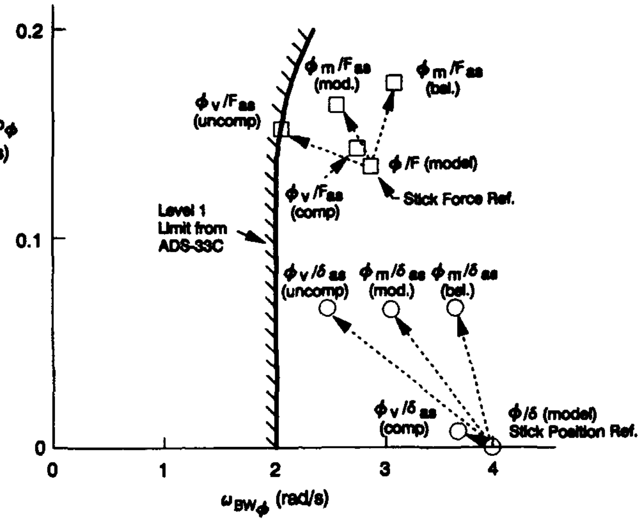


Figure 7. Migration of Bandwidth Parameters as Stick Force/Deflection, Visual, and Motion Effects are Introduced

TASKS

Seven tasks were evaluated, consisting of precision and aggressive maneuvers at hover and in low-speed flight as defined by Section 4 of ADS-33C. The task layout and performance requirements are shown in Fig. 8. The precision tasks were a one-minute hover, vertical translation (a surrogate for landing), and pirouette. The aggressive tasks were the bob-up/bob-down, dash/quickstop, and sidestep. A 40-kt lateral slalom task, which has no counterpart in ADS-33C, was included to emphasize a combination of precision and aggressiveness. Desired and adequate performance limits were defined for each task, based as much as possible on ADS-33C limits but adapted when necessary to the specific visual environment of the DIG. Not all tasks were flown for all configurations; the full scenario was used for evaluations of the competing sets of motion systems and for evaluation of the Usable Cue Environment, but most evaluations of time-delay effects were typically limited to the hover, vertical translation, slalom, and bobup/bobdown. Cooper-Harper Handling Qualities Ratings[19] (HQRs) were assigned for each task. Seven pilots, with varying backgrounds and levels of experience, participated in the simulation.

RESULTS

Figure 9 is a summary plot of the HQRs for the seven evaluation tasks. Average HQRs are depicted by solid symbols that are connected by a solid line for clarity. Each data symbol represents a single rating. The variations in motion and visual delay compensation have been arranged in order of generally improved average HQRs.

Since the ultimate validation of the simulation results is their correspondence to flight data, ratings from a similar flight experiment[2] are shown in Fig. 9 for the hover, vertical translation, dash/quickstop, and sidestep tasks. These ratings were obtained with the Canadian National Research Council's variable-stability Bell 205A helicopter; task performance requirements in all cases were similar to the simulation, with the exception of the vertical translation, where actual landings were performed in the flight experiment. The comparison configuration from the flight experiment is for a Rate Response-Type with pitch and roll attitude Bandwidths comparable to the simulation model. The HQRs from the flight experiment are averages and spreads (maximum and minimum) from five pilots.

<u>Effect of Task.</u> There is evidence in Fig. 9 of rating differences across the tasks. Generally, the easiest tasks (in terms of best HQR for all combinations of motion and visual) were the hover, bobup/bobdown, and dash/quickstop. Since no turbulence, gusts, or winds were simulated, the one-minute precision hover was low-workload as long as the helicopter was reasonably well stabilized before starting the formal maneuver. Pilot comments indicated that the bobup /bobdown was relatively easy because of the decoupled helicopter model, making this almost entirely a

MANEUVERS	DESIRED PERFORMANCE	ADEQUATE PERFORMANCE
20 ft Hover (1 minute)		
Position	Keep Cone in Window	Cone in Window 60% of Time
Altitude	±2 ft	±5 ft
Heading	±5°	±10°
Vertical Translation		
Position	Same as Hover	Same as Hover
Altitudes	Same as Hover	Same as Hover
Heading	Same as Hover	Same as Hover
Pirouettes		
Position	±10 ft	±20 ft
Altitude	±5 ft	±10 ft
Heading	Pointed at Center	Pointed at Center
Time	45 s	75 s
Slalom		
Position	Δy < 3 Squares	Don't Hit Poles
Airspeed	+3, -5 kts	-5 kts
Altitude	±15 ft	+30, -20 ft
Bobup/Down		
Altitude (Up)	±6 ft	±12 ft
Altitude (Down)	-5 ft	-10 ft
Time	12 s	18 s
Dash/Quickstop		
Position	Past last pole, before sidestep stripe	Past next to last pole before sidestep stripe
Altitude	±15 ft	±25 ft
Sidestep		
Position	±20 ft	±28 ft
Altitude	±10 ft	±20 ft
Heading	±10°	±20°

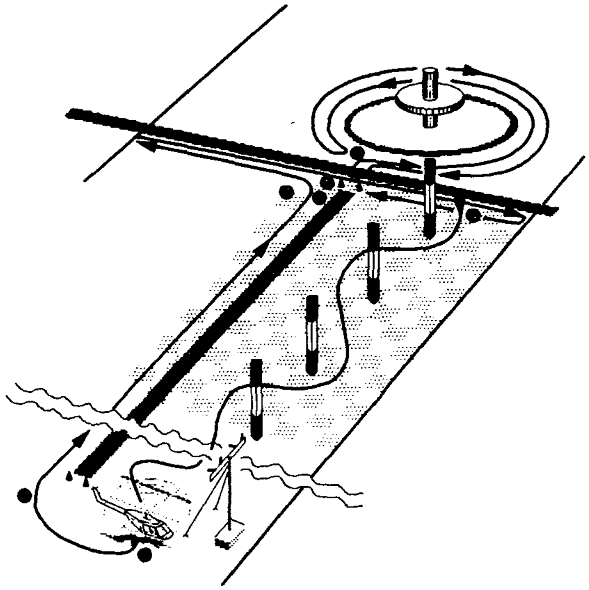


Figure 8. Tasks

single-axis task, while the dash/quickstop was rated well because of the ample forward field-of-view for initiating the maneuver. By contrast, the vertical translation, pirouette, and slalom maneuvers were inherently multi-axis and thus tended to receive higher HQRs, while pilot comments indicate that the high ratings for the sidestep maneuver are due primarily to the lack of a sideward field-of-view for adequately determining the endpoints of the maneuver.

<u>Effect of Visual Delay Compensation (Fixed Base).</u> The first two sets of HQRs in each part of Fig. 9 are for fixed-base evaluations. The primary tasks evaluated fixed-base were the hover, vertical translation, and slalom. In the absence of motion, the pilot's only feedback of aircraft response is visual, so the effect of adding the visual compensation filter is equivalent to removing 83.3 ms of pure time delay in the visual path. As one would expect, the HQRs generally improve when the filter is on. A direct comparison of HQRs is difficult, however, since the compensation-off evaluations were made by only three pilots, including Pilot H, who did not fly any other motion/visual combination.

<u>Effect of Visual Delay Compensation (Moving Base).</u> The effects of the visual compensation filter were evaluated moving-base by turning the filter on with the Baseline set of motion washout filters. There is a trend for improved ratings in Fig. 9 when the filter is added in this situation as well; examination of individual ratings is possible here, however, and these HQRs are discussed in more detail later in this paper.

<u>Effect of Motion vs. Fixed Base.</u> The benefits of motion are evident in Fig. 9: for most tasks, the average HQRs improve by about one rating point when motion is added (compare especially the visual-compensation-on ratings, fixed-base, with either of the moving base washout cases). It is especially significant to note that motion is required to obtain Level 1 average HQRs for a helicopter model that was designed to be Level 1 by the requirements of ADS-33C. Only the vertical translation and sidestep maneuvers have average HQRs worse than 3.5 moving-base, while none of the tasks received an average HQR better than 3.8 fixed-base.

<u>Baseline vs. Modified Motion Washouts.</u> Comparison of the HQRs for the Baseline set of motion washouts and gains and the Modified set in Fig. 9, both with visual compensation on, shows a general trend for slightly improved ratings with the Modified set. There are exceptions, however, as the average ratings for the bobup/bobdown and sidestep tasks are slightly worse. The slight improvements for the other tasks suggest

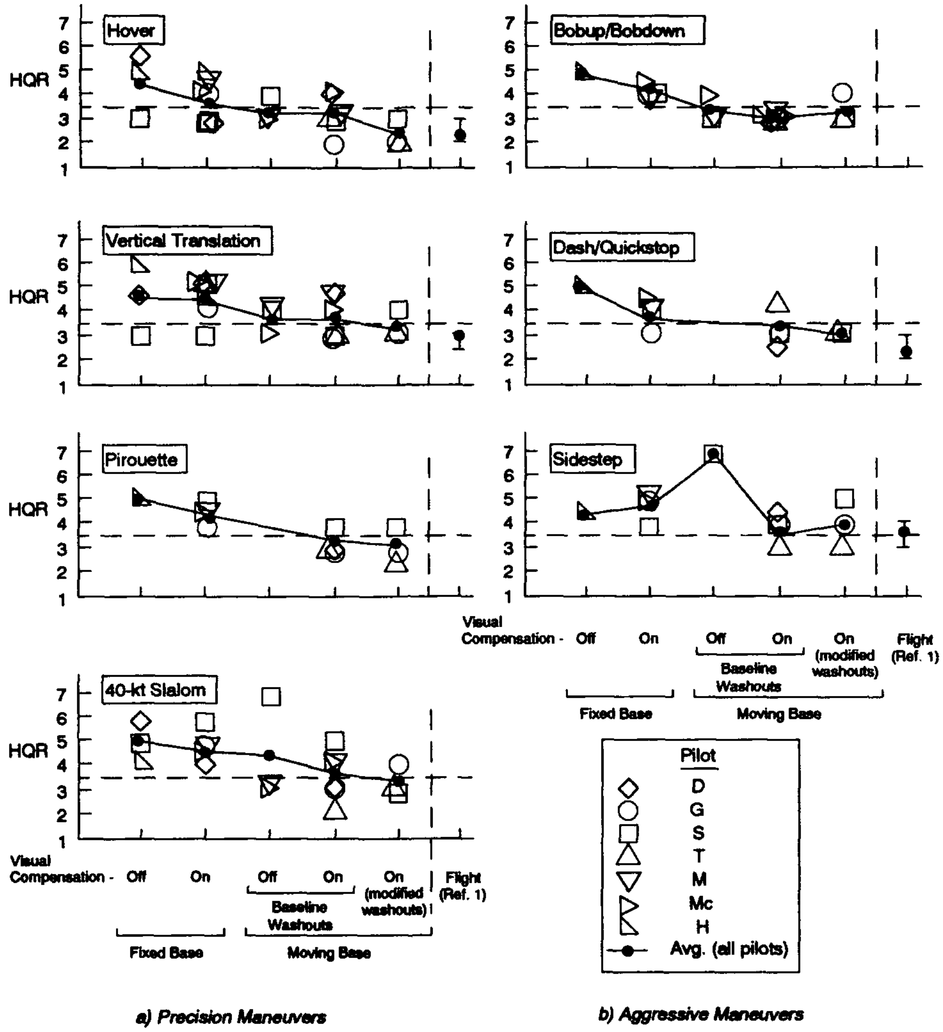


Figure 9. Summary of HQRs

that the pilots were either aware of the more consistent motions provided by the Modified set, or, conversely, that the rapid washouts of the Baseline set mitigated the beneficial effect of the increased initial accelerations provided by the higher gains. It is likely that the answer is a blend of the two, supported by the degraded ratings for the bobup/bobdown (where initial accelerations are an important cue to the pilot) and the sidestep (where the Modified motion washouts overdrove the vertical axis in response to lateral commands).

By their nature, aggressive tasks involve rapid changes of state — i.e., large initial accelerations — compared to the precision tasks. Since the Baseline motion gains transmitted more of the initial acceleration onset cues, it might be expected that this set would be preferred for the aggressive tasks, and this is the case for the bobup/bobdown and sidestep (Fig. 9b). By contrast, the Modified motion set was designed to provide more accurate phasing of the motion and visual responses, at the cost of reduced gain. Therefore, it is reasonable to expect this system to be preferred for those tasks

that involve continuous closed-loop operations, such as the precision tasks, and this is the case as well (Fig. 9a).

Several important factors must be considered in comparing the HQRs for the two motion gain/washout sets: first, the Modified set as developed for this simulation was intended to be exploratory in nature, and it did not take advantage of all axes (see Table 1); and second, since the basic aircraft was good to begin with, small changes in average HQR may or may not be significant. Further testing is required, especially to determine the possible effects of motion washouts when the handling qualities are degraded to begin with, i.e., for a Level 2 or 3 helicopter.

The Modified-motion evaluations were performed by three pilots (Pilots G, S, and T). In their commentary, Pilots G and T expressed a slight preference for the Modified set, while Pilot S preferred the Baseline gains and washouts. Pilot G, a highly experienced former NASA test pilot with many hundreds of hours in the VMS, did not indicate any dissatisfaction with the Baseline set. He was able to discern the differences between the two gain sets:

> I sense from my initial evaluation [of the Modified washouts], as well as going through these formal evaluation tasks, that you have washed out some of the motion.... I like it. This is fine. I thought the [Modified] motion system gave me good cueing compared to the [Baseline].

By contrast, Pilot T found the Baseline washouts and gains to be inadequate, expressing a preference for the Modified set:

> There's a slight, very subtle increase in the value of the motion system. There's something about it that is just a little bit better for me.... It's either the feel on the seat of the pants or the correlation between motion and the eye, it's hard to tell.... I think the motion cues are just a tiny bit better on this system.

Pilot S's comments on the Baseline and Modified washouts are similar for most tasks. Pilot S had a tendency, however, to reach software motion trips more frequently with the Modified set, and his commentary indicated a strong negative reaction to this.

Comparison With Flight. As a final measure of the effectiveness of the piloted simulation, the ratings from the similar flight experiment[1] can be compared to the best of the simulation results. The data of Fig. 9 show a generally greater rating spread from the simulation than from flight, a result that is consistent with previous studies (e.g., Fig. 1). In addition, the average HQRs for the in-flight evaluations are slightly better, indicating that the best of the simulation motion/visual combinations is still not quite on par with the flight experiment. An exception is the hover, where the ratings spread and averages for flight and simulation (moving-base, Modified washout set) are almost identical.

Effects of Visual vs. Model Delay. The effects of the location of added time delay were investigated in two ways. The first method was to simply turn the visual compensation filter off. Since the filter provides an effective 83.3 ms of lead to compensate for the generation of visual images by the DIG, removing this filter is equivalent to introducing 83.3 ms of time delay in the visual path only, and therefore the model and motion system responses are unchanged. For comparison, an 80-ms pure delay was introduced in the time-delay circuit in the model software, thus affecting the entire simulation — model, motion, and visual. Several evaluations were made with both of these sources of time delay.

Figure 10 shows individual and average HQRs for the four primary evaluation tasks for the no-delay case (visual compensation on, no added delays), for visual-only delay (compensation off), and for total model delay of 80 ms. The Baseline motion washouts and gains were used for all evaluations. There is a slight degradation in average HQRs for either source of delay. With the exception of the slalom task, the degradation is less when the delay is in the visual path only. The spread in HQRs for the slalom with visual delay indicates large scatter: two pilots rated this better than with the compensation filter on (HQRs of 3 and 3 compensation off, and 4 and 4 compensation on), while the third gave the visual-delay case an HQR of 7.

It is significant that the degradation in HQRs is such that Level 2 average ratings (moving-base) result when the total added delay is only about 80 ms. This value of delay corresponds almost exactly to the point at which the Bandwidth of the visual response to control force inputs falls into the Level 2 region in the requirements of ADS-33C (e.g., ϕ_V/F_{as}, uncompensated, Fig. 7).

Figure 10 includes HQRs from all pilots, even though only one of the seven flew all three of the time-delay variations. In terms of the added-delay evaluations, Pilots M, Mc, and S flew the visual-only case; two (Pilots M and Mc) generally preferred the visual-delay case over the no-delay case, while the third (Pilot S) was just the opposite.

Comments by Pilot S for the visual-delay case deal almost exclusively with motion problems, rather than

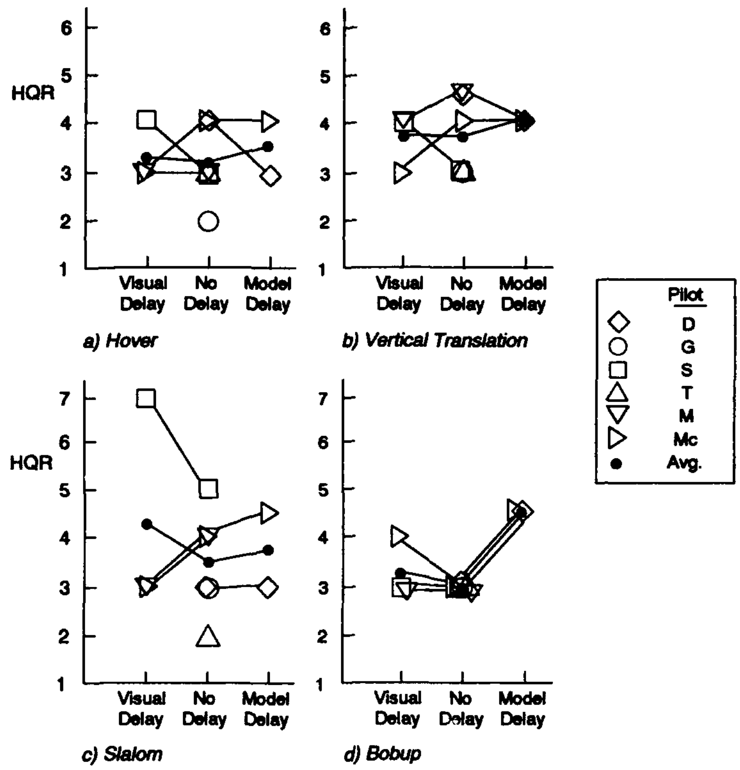


Figure 10. Effects on HQR of Introducing Approximately 80 ms of Time Delay in the Visual Scene Alone (Visual Delay) and in the Total Simulation Model (Model Delay). Baseline Motion Washouts

visual. It is not clear whether the adverse comments about motion for these evaluations reflect the change in the motion/visual relationship, or simply Pilot S's dissatisfaction with the motion response.

Pilots M and Mc had relatively little previous exposure to ground-based simulation. These pilots generally preferred the visual-delay case over the no-delay case because of the reduction in crispness of the response. For Pilot M,

> This [visual-delay case] was the least as far as the crispness goes.... This last one is more in tune....It was easier to control.

Pilot Mc did not specifically comment on the visual response; instead, his comments for each task show a consistent difference between the no-delay case and the visual-delay case. For example, with no delay, for the hover "The problem is continuous small corrections in the lateral and longitudinal cyclic required to maintain your position. I'd say one or two in both directions every second to keep the [hover reference] cone from wandering a lot [HQR 4];" while with visual delay, "it almost hovers by itself. You only have to compensate for drift once every five or six seconds [HQR 3]." Pilot Mc also made a general comment for the visual-delay evaluations that "The motion and the visual system seem to be more in line with each other than before. The aircraft seems to be more damped."

There was also a difference of opinion when the time delay was located in the model, thus producing a uniform 80-ms delay. Of the two pilots who flew this case, Pilot D generally showed indifference to the added delay—his HQRs improved for some tasks and degraded for others (Fig. 10). For Pilot Mc, however, there was a degradation in HQR with time delay for all but the hover task, where the same rating was assigned for both the no-delay and the model-delay

cases. Pilot Mc flew this configuration immediately after the visual-delay case, and his overall comments reflected his opinion of both:

> [With visual compensation off] I thought it was crisp, and I could be very precise on what I wanted it to do. The second one [80-ms model delay] didn't seem to be as stable.... It wasn't as crisp, but it wasn't sluggish.... The [visual-delay case]..., overall, felt more like flying than any of the others.... The motion and visual cues seemed to be the most consistent between my inputs, and the aircraft response, and what happened on the outside.

Based solely on the HQRs and comments for Pilot Mc, there is evidence that it is better to turn the visual compensation filter off, and that time delays in the visual scene are not equivalent to time delays in the overall simulation. There is some rationale for this, since the high-frequency response of the visual scene with the compensation filter turned off exhibits approximately 93 ms of total delay from cockpit to screen, and the VMS cab motion exhibits 90 ms of effective delay dues to high-frequency lags. Thus the visual (with compensation removed) and the motion responses are nearly in phase, whereas the implementation of the visual filter actually increases the discordance between visual and motion responses (Fig. 6). On the other hand, the HQRs of Pilot S are exactly opposite those of Pilot Mc, suggesting that the pilots' HQRs were heavily influenced either by their preconceptions of how the helicopter should fly, or by their experience (or lack of experience) with flying the VMS. Neither hypothesis can be resolved using the data generated here, and it is clear that more simulation time will be required to determine any concrete, consistent differences.

CONCLUSIONS

This study of the interactions of simulator motion, visual, and response dynamics on rotorcraft handling qualities has both confirmed previous observations and revealed areas deserving of more indepth study. Unlike most previous motion/visual simulation studies, the primary goal of this study was the measurement of these interactions on perceived handling qualities, rather than on objective performance measures.

Motion was necessary to obtain satisfactory handling qualities: none of the tasks received Level 1 average HQRs fixed-base. Improvements in HQRs when motion was added were generally 1/2 to 2 rating points.

Based on average HQRs, a modified set of gains and washouts, with low break frequency and low response gain, was slightly better for the precision maneuvers: hover, vertical translation, pirouette, and slalom. The baseline motion washouts received slightly better average HQRs for the bobup/bobdown and sidestep tasks, both classified as aggressive maneuvers in ADS-33C. Thus, the higher onset accelerations of the baseline set may be preferable for aggressive tasks.

Pilot ratings for the best combination of visual compensation and motion approached those received in a similar flight test experiment. The simulator ratings were slightly worse, with a larger interpilot rating spread.

Pilot opinion was mixed on the value of a visual delay compensation algorithm, with two pilots generally preferring it off and one preferring it on. The effect of visual delay on average HQRs was generally less than the effect of an equivalent overall transport delay.

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INITIAL VALIDATION OF AN R&D SIMULATOR WITH LARGE AMPLITUDE MOTION

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SUMMARY

The Advanced Flight Simulator (AFS) Complex at DRA Bedford has been enhanced by the addition of a large displacement motion platform and a three channel Computer Generated Image (CGI) outside world visual system. The trial described in this report was the first in a series of trials aimed at validating the AFS in its present configuration and in particular at demonstrating its ability to address a wide range of vehicle handling qualities with a high degree of fidelity and user confidence. It included a direct comparison between the ground-based AFS and the Calspan Learjet in-flight simulator.

The comparison between the AFS and Learjet involved three pilots flying the same offset approach landing tasks using the same aircraft model in both the AFS and in flight. The lateral handling qualities were varied by adjusting the time constant of a filter in the pilot's roll control loop. Pilot comments, handling quality and PIO ratings indicate that the AFS reproduces the lateral handling qualities and roll PIO tendencies of the Learjet in-flight simulator with high fidelity. The degradation in handling qualities and increase in PIO tendencies with increasing filter time constant were clearly revealed in both the AFS and Learjet. The importance of good platform motion cueing and task design when evaluating handling qualities was also demonstrated.

1. INTRODUCTION

The majority of modern fly-by-wire aircraft have exhibited some degree of handling deficiency during early flight testing which have ranged from undesirable to catastrophic. Examples include: the YF-16 which developed a pitch PIO during its first high speed taxi trials, converting to a roll PIO when the pilot decided to take off which resulted in both wing tips alternately hitting the runway before the aircraft safely climbed away; the Space Shuttle which developed a pitch PIO the first time it was landed on a runway rather than a dry lake bed, requiring the pilot to release the stick to stop the PIO; the Tornado which was well into its flight test development programme before it developed a PIO in the flare resulting in a heavy landing and major damage; and the first prototype JAS39 Gripen which developed a pitch PIO when landing and crashed. Clearly, the confident elimination of such handling problems before a vehicle flies would be highly cost effective.

The complexity and expense of modern fly-by-wire aircraft have increased the importance of, and reliance placed upon, piloted flight simulation in the design process. However, before simulators can be used with any confidence for the development and evaluation of handling qualities, the fidelity with which they can reproduce the flight handling characteristics must be demonstrated and their limitations understood.

The Advanced Flight Simulator (AFS) Complex at Bedford is constantly being updated and modified to meet ever increasing user requirements. Recent enhancements to the facility have resulted in greater changes than normal requiring a reappraisal of the simulator's fidelity and validity as a flying qualities research tool. These enhancements have included a 5-axis large displacement motion system, a 3 channel Link-Miles IMAGE IV Computer Generated Image (CGI) outside world visual system and the optimisation of the computing hierarchy to minimise throughput time delays. A series of trials aimed at establishing the level of validity of the AFS in this configuration was therefore planned and lateral handling qualities and the landing approach task were chosen for the first validation trial.

The trial was split into two phases. In the first phase (Ref 1), part of an experiment performed by Calspan (Ref 2) several years ago using their NT-33A in-flight simulator was replicated. This experiment examined the effect of high order control systems on the lateral handling qualities of a variety of aircraft configurations in an offset approach and landing task.

This paper concentrates on the results from the second phase (Ref 3), which directly compared the same vehicle model in the ground-based AFS and Calspan Learjet in-flight simulator using the same pilots in an offset approach and landing task. A major point of interest was how well the AFS could predict the occurrence of lateral pilot induced oscillations (PIOs).

2. THE ADVANCED FLIGHT SIMULATOR

2.1 Role and Capability

The AFS (Figs 1 and 2) is the latest development of the research simulator complex that has been in existence at Bedford for more than 30 years.

The key features of the AFS today are:-

- Reconfigurable cockpits, with programmable control feel and programmable aircraft quality Head-up Displays.
- Computer-generated and TV-based outside world visual scenes.
- Large and small motion platforms. The Large Motion System (LMS) is unique in Europe.
- Ease of use and easy access for researchers who are not simulation specialists. It accepts Users' models.

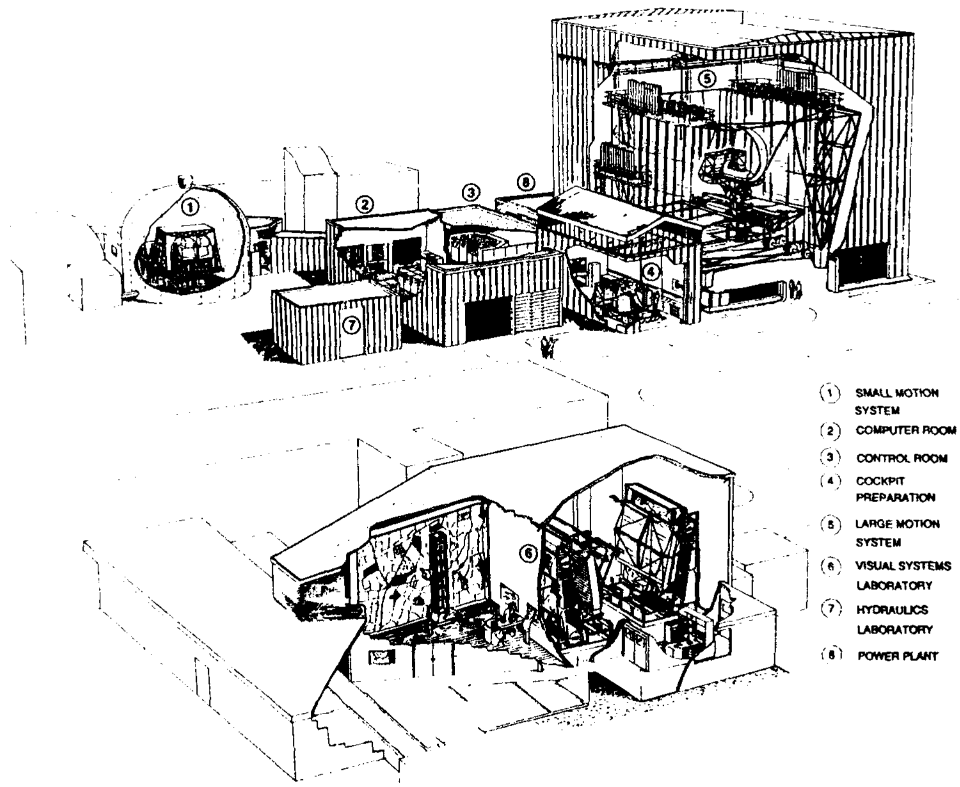


Fig.1 Schematic diagram of the simulator complex at DRA Bedford

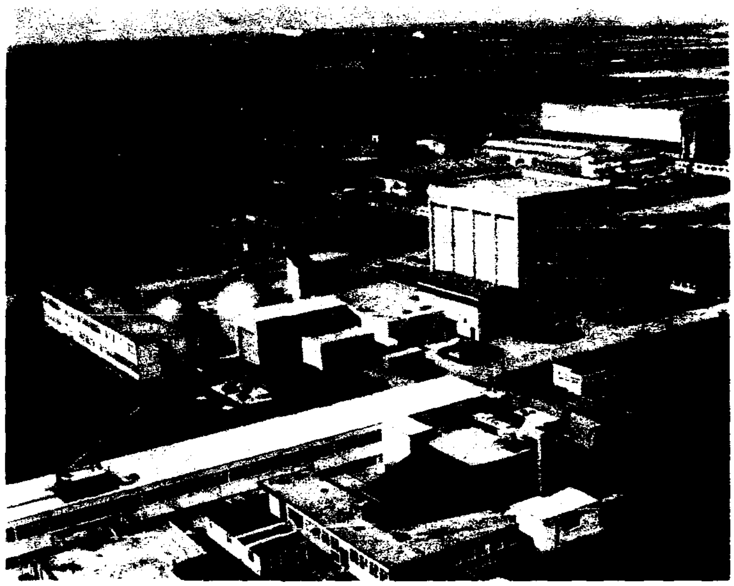


Fig.2 Simulator complex at DRA Bedford

The AFS simulates all kinds of vehicles (fast-jet aircraft, vertical take-off and landing aircraft, helicopters, transport aircraft and, potentially, both land and water-borne vehicles) with high cueing fidelity, to provide vehicle and systems designers with a representative environment in which to investigate the dynamic interaction between the pilot and the aircraft.

The AFS provides versatility and ease of use through alternative cockpits and cockpit internal layouts, and through a software environment which minimises the need for specialist knowledge. During experimental trials it is normally operated by individual researchers with little or no assistance from simulation specialists. Operationally, the AFS is unique among research simulators: its flexible software and hardware environment allows several separate and different vehicles to be simulated each day.

AFS cockpits can be interchanged for use on either of the available motion systems, or for use fixed-base. Internally, cockpits can be equipped with a variety of inceptors including conventional sticks and rudder pedals with programmable control force loading, side sticks, variable-feel collective and cyclic, controllable throttle-box/speed-stick, and variable and programmable Head-up and Head-down displays.

Outside world visual cues are generated either by a single channel TV-based system with alternative terrain models (700:1 & 3000:1 scales), which are selectable on-line by the researcher, or by a 3-channel computer-generated image system, or by a combination of both. The CGI system is an IMAGE IV from Link-Miles, a day/night/dusk system with full planar texture. Presentation of the visual scene is on collimated monitors.

The Large Motion System (LMS) is a unique component of the AFS. It provides motion in 5 axes: roll, pitch, yaw, heave and sway or surge. The choice between sway or surge is achieved when the cockpit is attached to the motion system and may be readily altered, in a few hours, to suit the needs of the current study. Fig 3 shows a photograph of a cockpit mounted on the LMS in Sway mode. The LMS performance limits are summarised in Table 3. Noteworthy features are the large linear displacements and the high velocities and the lively accelerations of all axes. Compared with the widely used 6-leg motion systems used by many training (and some research) simulators, the LMS is notable for the fact that the performance given in Table 3 may be achieved for all axes simultaneously as there are no interactions to inhibit the motion that may be demanded.

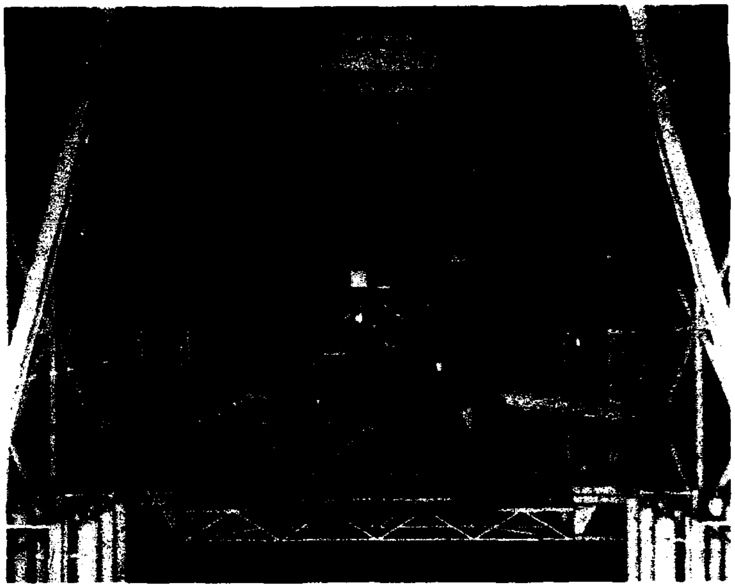


Fig.3 Cockpit in the 'sway' mode on the LMS

2.2 Motion Cueing

Motion cues are generated by a combination of software and hardware (Fig 4). The software embodies the cueing algorithm, also known as the washout logic, and some technique to ensure that demands fed to the motion mechanism are physically realisable. The hardware, or motion mechanism, defines the axes of motion available, the physical displacements and other performance parameters such as the maximum accelerations, maximum velocities and frequency response.

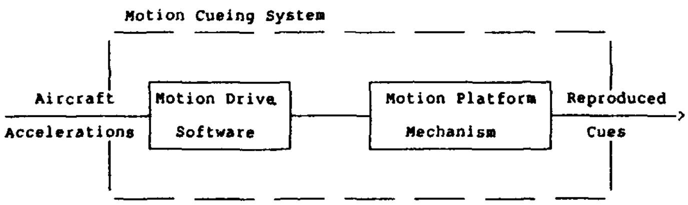


Fig.4 Motion cueing system

Currently, the motion drive algorithm employs linear second order washout filters in all axes, with built-in limit logic to ensure that, if the aircraft manoeuvres potentially demand too much of the motion mechanism, then appropriate limits are applied, ie:-

- If the acceleration is too high, it is limited to the maximum performance of each axis.
- If the velocity is potentially too high, a counter-acceleration is applied to ensure the permitted maximum velocity is not exceeded.
- If the combination of current velocity and current position is such that the maximum displacement would be exceeded, a counter-acceleration is applied to keep the machine within bounds.

The machine will always be brought to a smooth halt within the permitted excursions, and will resume its movement as soon as the excessive demands have reduced.

Details of the behaviour of the second order filter and its built-in limits are contained in Ref 4.

In each axis, the software (via washout break frequencies) sets the lower bound to the range of frequency over which motion cues can be generated with good fidelity, while the hardware natural frequency sets the upper bound (Fig 5). The choice of washout break frequency is principally determined by the available travel and velocity limits of the hardware: the greater the travel, the lower (and better) the washout break frequency can be.

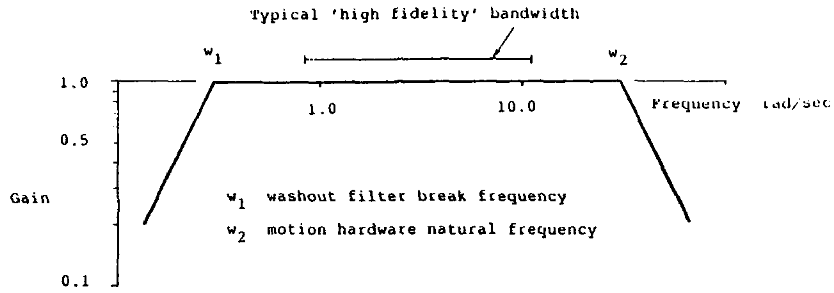


Fig.5 Reproduced motion in frequency domain

Phase considerations are important. At the washout break frequency, the phase is 90 degrees lead for a second order washout filter. This lead is only reduced to an acceptable level of 30 degrees or less at approximately 3 times the washout frequency. At the high frequency end, the phase due to the motion hardware is 90 degrees lag at the natural frequency and only 30 degrees or less at approximately 0.36 times the natural frequency. The combination of these two factors and the hypothesis that "phase distortions should be less than 30 degrees (lead or lag)" accounts for the 'high fidelity' bandwidth illustrated in Fig 5 being less than the nominal, a point made in an earlier paper (Ref 5).

The schematic in Fig 6 shows the principal components of the complete motion drive algorithm. The two main pathways are replicated for the various axes.

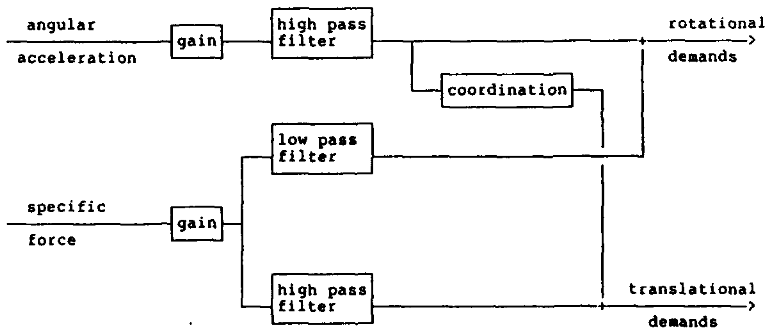


Fig.6 Simplified schematic of motion drive law

As the simulated aircraft flies and manoeuvres its angular accelerations in pitch, roll and yaw are fed to high pass filters and then to the rotational axes of the motion platform. The linear accelerations, here shown as specific force (acceleration minus gravity), are fed to both high pass and low pass filters. The high pass components are passed on to the translational axes of the motion platform. The low pass components of X and Y accelerations are fed to pitch and roll to simulate long term linear accelerations by cockpit tilt. False cues induced by deliberate cockpit roll (or pitch) can be compensated by coordinated sway (or surge). Given that the LMS cannot employ sway (Y) and surge (X) simultaneously, only one of these coordination signals can be used at any one time. A further term, not shown in the diagram, transfers the effective axis of roll (or pitch) to the correct location by use of sway (or surge). The 'gains' are really attenuation parameters, since they are normally less than the ideal value of 1.0.

All the motion software is fully parameterised to suit the research environment. This allows:-

- Tuning of all components by on-line variation of gains and washout frequencies.
- Isolation of components by setting transfer parameters to zero.

The motion software performs many other control functions but has been engineered to allow the substitution of alternative cueing algorithms within a standard control framework.

3. TRIAL DETAILS

3.1 Cockpit Environment

The cockpits of the Learjet and the AFS have little in common in a physical sense. The Learjet is a two-seat business jet while the AFS cockpit is configured for single-seat fast-jet operations. In addition, a helmet was worn (for safety reasons) in the AFS, but not in the Learjet. For a handling study, however, the flying qualities of the vehicle and the pilot/vehicle interface are considerably more important and these were replicated. The subject pilot occupied the right-hand seat in the Learjet and used a fighter-type centre-stick in both the Learjet and AFS.

Stick force was used as the command input to the vehicle model. The static and dynamic characteristics of the stick were nominally the same in the AFS and Learjet. The spring gradient was defined to be 6 lb/in longitudinally and 4 lb/in laterally, based on a mid-grip location, and in both axes the natural frequency was nominally 13 rad/s with a relative damping factor of 0.7. Breakout forces, freeplay and static friction effects were negligible. There were differences in stick geometry, particularly lateral stick which was significantly shorter in the AFS, but this did not appear to be a problem to the pilots.

No attempt was made to match the instrument layout of the AFS cockpit to the Learjet, but the main instruments (ADI, ASI, altimeter, VSI and engine tachometer) were provided.

3.2 Model Definition

Parameter identification of the Learjet was considered to be desirable as a means of ensuring a common baseline configuration for both the in-flight and ground-based simulators, but this could not be achieved within the time constraints. After further discussions with Calspan, Configuration L2-2 from Reference 2 was selected as the baseline configuration. This configuration has a steady-state roll rate of 10 deg/s per pound stick force and a roll mode time constant of 0.45s. In order to achieve these values however, it became apparent that the aircraft would need to be in a low-fuel state, severely restricting useful sortie time. The configuration actually used has a steady-state roll rate of 7 deg/s per pound stick force and a roll mode time constant of 0.6s and is fully defined in Table 1. The only experimental variable was the time constant of a first order lag filter in the pilot's command path, ie between stick and control surface, representing control system dynamics. The longitudinal configuration, which is defined in Table 2, was chosen for its benign handling characteristics to prevent any intrusion into the lateral handling task. The dynamics and performance of the Learjet's engine were approximated in the AFS.

During the course of the evaluation (Sortie No 4), one pilot noted an adverse yaw effect (caused by sideslip when turning) which was not present in the aircraft (due to sideslip suppression) and which he believed prejudiced his handling assessment. Since it was not practical to [illegible] the in-flight simulator, a minimum sideslip version of the lateral model was implemented on the AFS and used for all subsequent assessments (Table 1).

3.3 Time Delays

Time delays are an important influence on aircraft handling qualities and any differences between the Learjet and AFS had to be accounted for and if possible minimised.

The Learjet has an analogue Flight Control System (FCS) with no pure time delays. However there are significant filtering effects which are perceived by pilots in a similar way to a pure time delay, and which can be lumped together into an 'equivalent' delay, estimated by Calspan to be 80ms* for the Learjet. B In addition, the minimum filter time constant used in the Learjet was 40ms, estimated to produce 45ms 'equivalent' delay.

The AFS is a hybrid system comprising digital (computing and CGI) and analogue (motion and g-seat) elements. The pilot's visual loop, in which all the elements are digital, was considered the most time-critical with a nominal pure time delay or latency of 125ms.

The time delay was therefore the same, at 125ms, when the minimum filter time constant is included for the Learjet, though of course for the Learjet the delay was 'equivalent' whilst for the AFS the delay was 'pure'. For the purposes of this paper, the datum delay is taken to be 80ms, ie the Learjet without the additional 40ms lag filter.

** Calspan has recently informed the authors that the equivalent delay of the Learjet is less than was originally estimated. Whilst the exact figure is still to be established, a reduction in Learjet datum delay would move all Learjet results to the left (dashed lines in Figures 7 to 10) giving an improved match with the AFS results for 7 of the 8 comparisons presented.*

Table 1

Definition of Lateral Model

Lateral Equations of Motion

$$\begin{pmatrix} \dot{v} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \end{pmatrix} = \begin{pmatrix} y_v & (y_p + w_o) & (y_r - u_o) & g\cos\theta_o \\ l_v & l_p & l_r & l_\phi \\ n_v & n_p & n_r & n_\phi \\ 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} v \\ p \\ r \\ \phi \end{pmatrix} + \begin{pmatrix} y_\xi & y_\zeta \\ l_\xi & l_\zeta \\ n_\xi & n_\zeta \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \xi \\ \zeta \end{pmatrix}$$

Lateral Derivatives at 125 knots

y_v	=	-0.12	(-0.119)	u_o	= 209 ft/s
y_r	=	-33.0	(-33.5)	w_o	= 27.5 ft/s
y_p	=	-6.0	(-6.25)	α_o	= 7.5°
n_v	=	0.0075	(0.0078)	θ_o	= 4.5°
n_r	=	-1.0	(-0.8727)		
n_p	=	-0.03	(0.0308)	y_ξ	= 0.0168
n_ϕ	=	0.0	(0.1074)	y_ζ	= -0.00595
l_v	=	-0.014	(-0.009)	n_ξ	= 0.02926
l_r	=	1.25	(1.054)	n_ζ	= 0.00181
l_p	=	-1.67	(-1.7983)	l_ξ	= 0.2814
l_ϕ	=	0.0	(-0.2047)	l_ζ	= -0.00031

Dimensions are slug, ft, sec and angles are in radians, except where stated. Control derivatives are expressed in terms of stick and rudder force where a positive force produces a positive moment, hence the sign and magnitude of the these derivatives. Bracketed terms denote changes made for the minimum sideslip version of the model.

Lateral modes (both models)

Real	Imaginary	Relative Damping	Frequency	Time Constant
-0.5397	1.393	0.3613	1.494	
-0.03996				25.0
-1.671				0.5984

Table 2

Definition of Longitudinal Model

Longitudinal Equations of Motion

$$\begin{pmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} x_u & x_w & -w_o & -g\cos\theta_o \\ z_u & z_w & u_o & -g\sin\theta_o \\ m_u & m_w & m_q & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} u \\ w \\ q \\ \theta \end{pmatrix} + \begin{pmatrix} x_\eta \\ z_\eta \\ m_\eta \\ 0 \end{pmatrix} \left(\eta\right)$$

Longitudinal Derivatives at 120 knots

$x_u = -0.041$

$x_w = 0.11$

$z_u = -0.26$

$z_w = -0.9$

$m_u = 0.0$

$m_w = -0.0226$

$m_q = -2.2$

$u_o = 205$ ft/s

$w_o = 25$ ft/s

$\alpha_o = 7.0°$

$\theta_o = 4.5°$

$x_\eta = 0.00046$

$z_\eta = 0.12$

$m_\eta = 0.04817$

Dimensions are slug, ft, sec and angles are in radians, except where stated. Control derivatives are expressed in terms of stick and rudder force where a positive force produces a positive moment, hence the sign and magnitude of these derivatives.

Longitudinal modes

Real	Imaginary	Relative Damping	Frequency
-1.545	2.048	0.6022	2.565
-0.02558	0.166	0.1523	0.168

3.4 World Environment

Learjet

When simulating an aircraft of similar size the Learjet has all the advantages of real flight, including full motion and visual cues. The AFS, like all ground-based simulators, has to generate these motion and visual cues artificially. This is clearly a major influence on the simulator's validity as a handling qualities research tool, which is why considerable efforts have been made to improve these in recent years. Conversely, ground-based simulators offer considerably better flexibility and may be used to explore safely a wider range of vehicle characteristics and operating environments.

AFS Motion Cueing

The Large Motion System (LMS) has three rotational and two translational degrees of freedom (heave and sway for this trial), with performance figures as shown in Table 3. The major parameters of the software drive algorithms are shown in Table 4.

Table 3

Large Motion System Performance

Motion Axis	Maximum Displacement	Maximum Velocity	Maximum Acceleration
Sway	±4.0m	2.5 m/s	5.0 m/s^2
Heave	±5.0m	3.0 m/s	10.0 m/s^2
Roll	±0.5 rad	0.7 rad/s	3.0 rad/s^2
Pitch	±0.5 rad	0.5 rad/s	2.0 rad/s^2
Yaw	±0.5 rad	0.5 rad/s	1.5 rad/s^2

Table 4

Major LMS Drive Algorithm Parameters

Motion Axis	Gain	Washout Frequency (rad/s)
Sway	0.2	0.3
Heave	0.2	0.5
Roll	0.3	0.35
Pitch	0.6	0.26
Yaw	0.3	0.3

Roll tilt implemented for low frequency side-force cueing.

A g-seat was also used during the evaluation, mainly to provide runway rumble effects. Motion cueing from the seat was minimal for the approach and landing task.

AFS Visual Cueing

The outside visual scene was generated by a Link-Miles Image IV CGI system and presented to the pilot on three collimated monitors. Conventional 625-line monitors were driven through custom-built interface units which guaranteed a consistent update rate of 50 Hz. However, the normal calligraphic light point capability was lost and the field of view was reduced slightly to 120° in azimuth and 30° (47° for the side monitors) in elevation. The resulting absence of PAPIs (Precision Approach Path Indicators) influenced the task on the AFS as discussed in Section 5.

A visual terrain database for the Bedford airfield was built specially for the trial. It contained a detailed representation of the main runway and major buildings in the vicinity.

Weather Conditions

On two of the aircraft sorties there was significant crosswind and turbulence. The wind strength and direction, and the level of turbulence, did not change greatly during these sorties and therefore average values were adopted for all approaches in the corresponding AFS sortie.

3.5 Landing Approach Task

The task consisted of a 3° glide-slope approach to DRA Bedford's Runway 27 using PAPIs, but offset to the right of the centre-line by half the runway width (150 feet). At 150 feet agl, the safety pilot (or simulator engineer) called for the landing manoeuvre to begin, at which point the evaluation pilot initiated an 'S' turn to land on, and parallel to, the runway centre-line. Desired lateral touchdown performance was defined to be within ±5 feet of the centre-line, and adequate performance to be within ±20 feet. Longitudinally, desired performance was defined to be within 250 feet (but not short) of an aim line painted across the runway adjacent to the PAPI lights, and adequate performance to be within 500 feet. Subjective ratings (Cooper-Harper and PIO) were based not just on touchdown performance but on the pilots' appraisal of their overall performance.

In the absence of PAPIs in the AFS, a talk-down procedure was adopted. The correction manoeuvre was always initiated at the same range (consistent with 150 feet on a 3° glide slope), accepting any height variation there might be.

4. TRIAL PROCEDURE

4.1 Pilot Background

Two of the pilots are Aerospace Research Squadron (ARS) test pilots based at DRA Bedford, and the third is a test pilot with British Aerospace. Pilots B and C have considerable experience of fighter-class aircraft. Pilot A's background is transport aircraft but he has test-flown fighter aircraft.

4.2 Evaluation Timetable

All three pilots flew practice sorties in the AFS to familiarise them with the task and rating scales. Two of the pilots (B and C) were able to fly their evaluation sorties (in-flight simulator followed by the ground-based simulator) on the same day. Pilot A did not fly his AFS evaluation sortie until four days later, although he did fly a practice sortie on the same day as his Learjet sortie.

4.3 Model Validity

During Pilot B's first evaluation sortie on the AFS (No 4), differences in aircraft directional behaviour became apparent. Specifically, the AFS model generated sideslip in turns (as does the agreed vehicle model) whereas the Learjet used sideslip suppression. The difference, though not great, was enough to cause Pilot B to compensate to an extent that the validity of this evaluation was considered to be compromised. The flexibility of the AFS enabled a modified AFS model, which minimised sideslip whilst retaining all other essential characteristics, to be implemented in time for Pilot C's assessment and Pilot B's second assessment. Pilot A's assessment was based on the original AFS model, but he considered that this model was a good match to the Learjet model and the evaluation went ahead on this basis. A second sortie allowing him to assess changes to the model's yaw characteristics confirmed that his control behaviour was unaffected and that his original assessment was valid.

4.4 Rating Scales

Two rating scales were employed. These were the Cooper-Harper Rating (CHR) scale (Ref 6 and Table 5) and a PIO rating scale (Table 6). Pilot comments were also collected, and to encourage these a check list was used.

Table 5

Cooper Harper Rating Scale

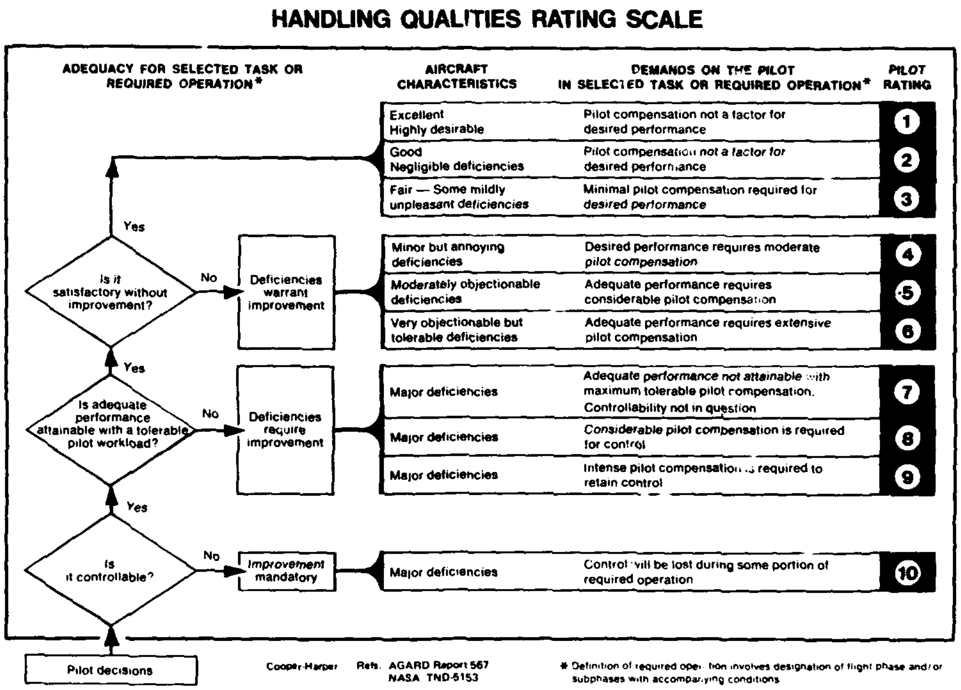
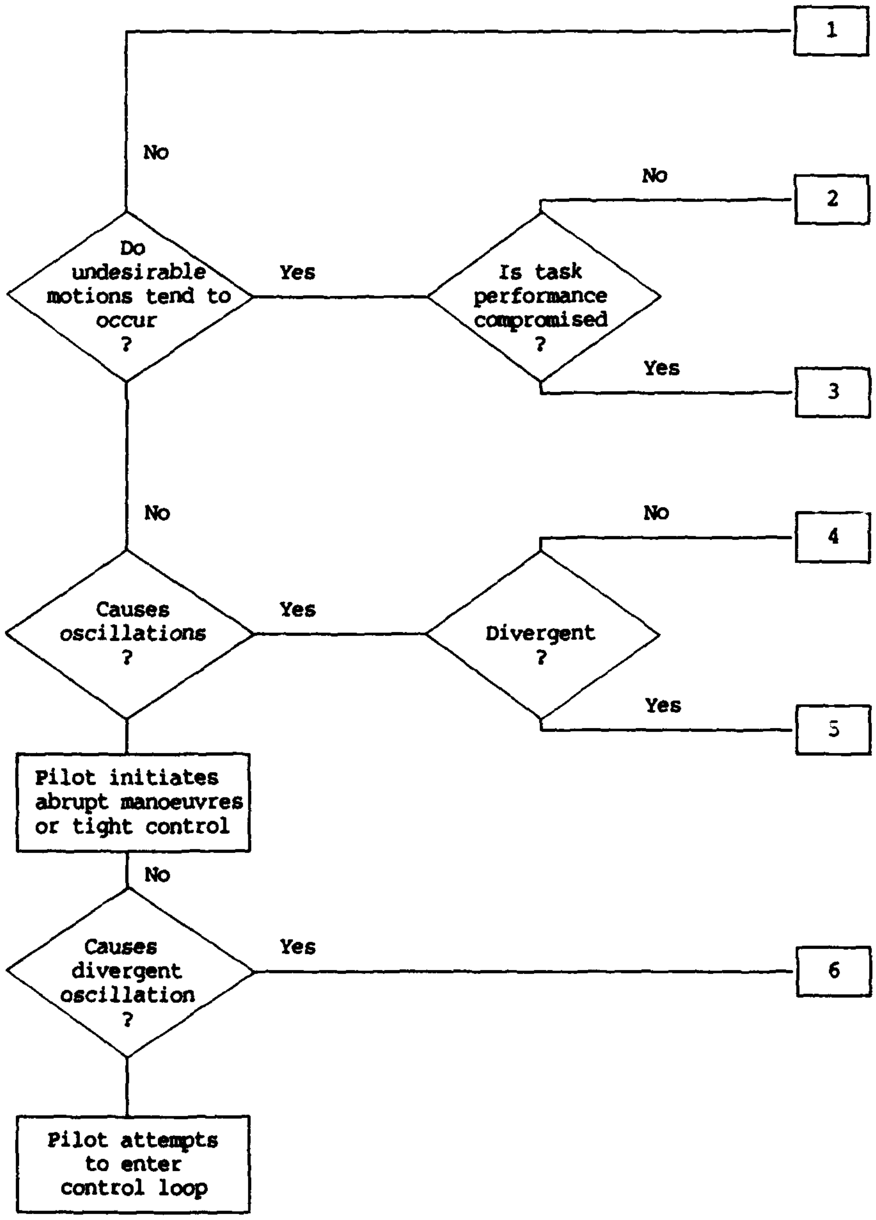


Table 6

PIO Tendency Rating Scale



5. DISCUSSION OF RESULTS

5.1 Validation of the AFS

The results of the subjective handling assessment are in the form of pilot comments, handling qualities ratings and PIO ratings. Second order polynomial functions (least squares error) have been fitted to all rating data to allow broad comparisons to be made between the in-flight and ground-based results. Figure 7 combines data from all directly comparable evaluation sorties. An analysis which compared only data for values of time constant flown on both simulators showed little difference. Figures 8, 9 and 10 show the individual rating data for Pilots A, B and C respectively.

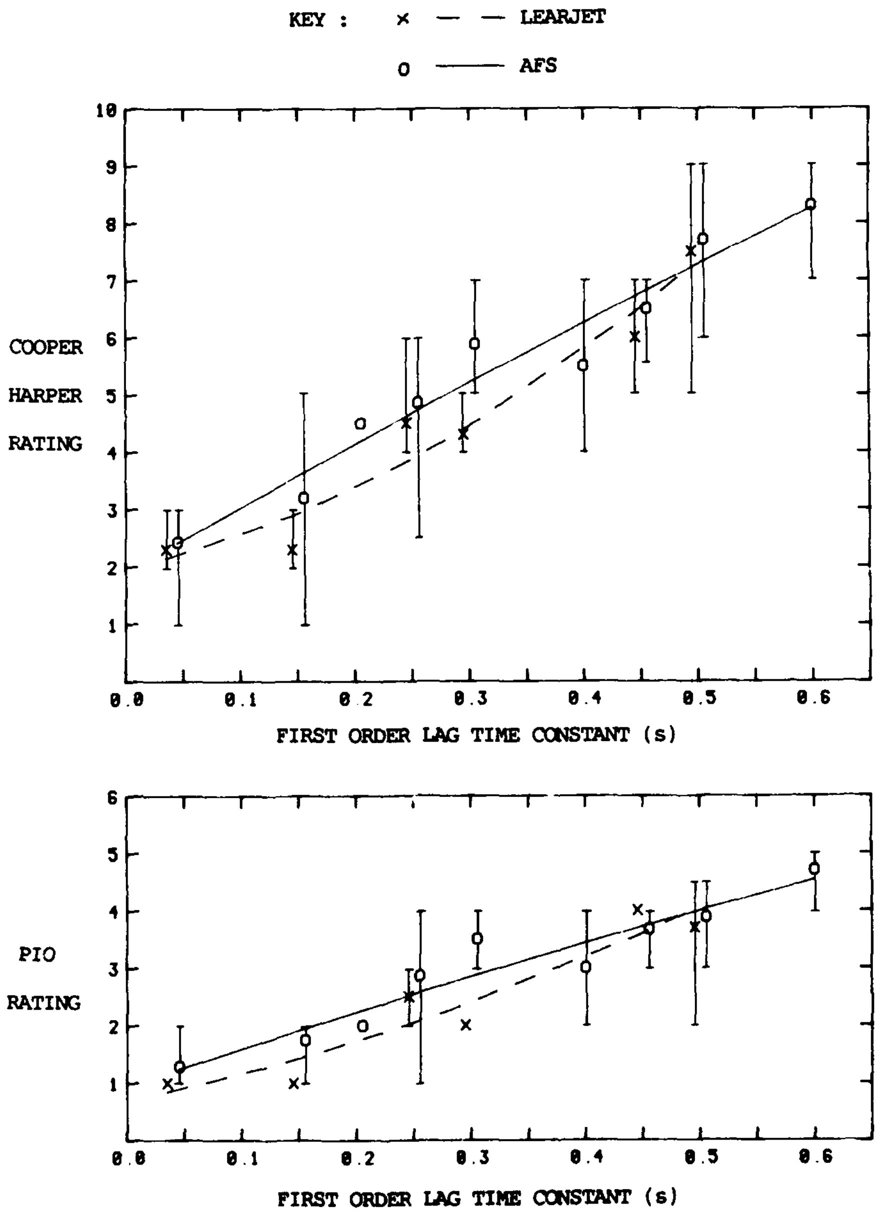


Fig.7 Mean pilot ratings (with maxima and minima) from the AFS and Learjet for the offset approach task

The rating data are consistent with pilot comments and show the following:-

1. There is close agreement between the results from the AFS and from flight.
2. The degradation in handling qualities and the increase in PIO tendency with increasing control system lag is clearly revealed both in the ground-based AFS and in flight in the Learjet.
3. The AFS is in most cases marginally more difficult to fly than the Learjet.
4. There is significant variabili y in ratings between pilots and between repeat configurations for the same pilot.
5. The variability tends to be g eater in the AFS than in the Learjet, but only a small number of replications were possible.

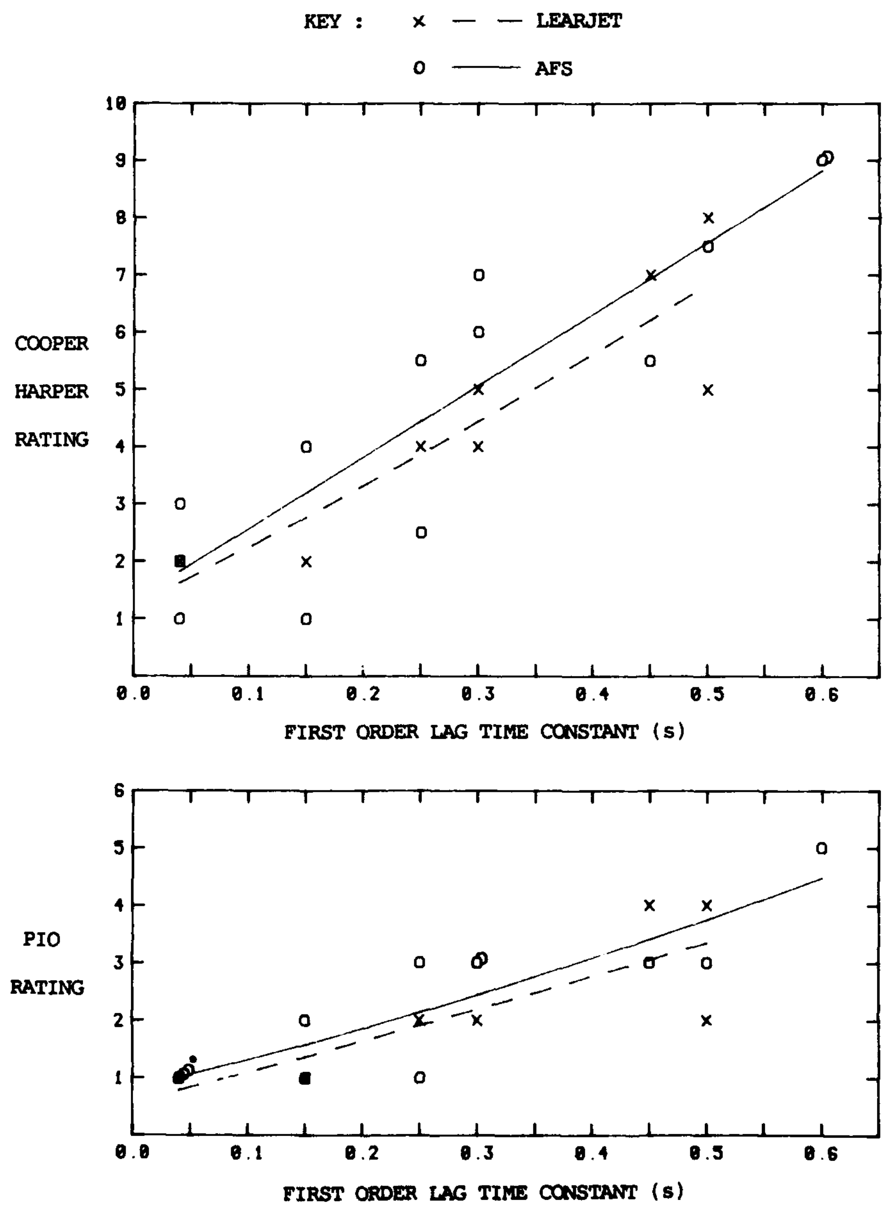


Fig.8 Pilot ratings from the AFS and Learjet for the offset approach task — Pilot A, Sorties 5 and 6

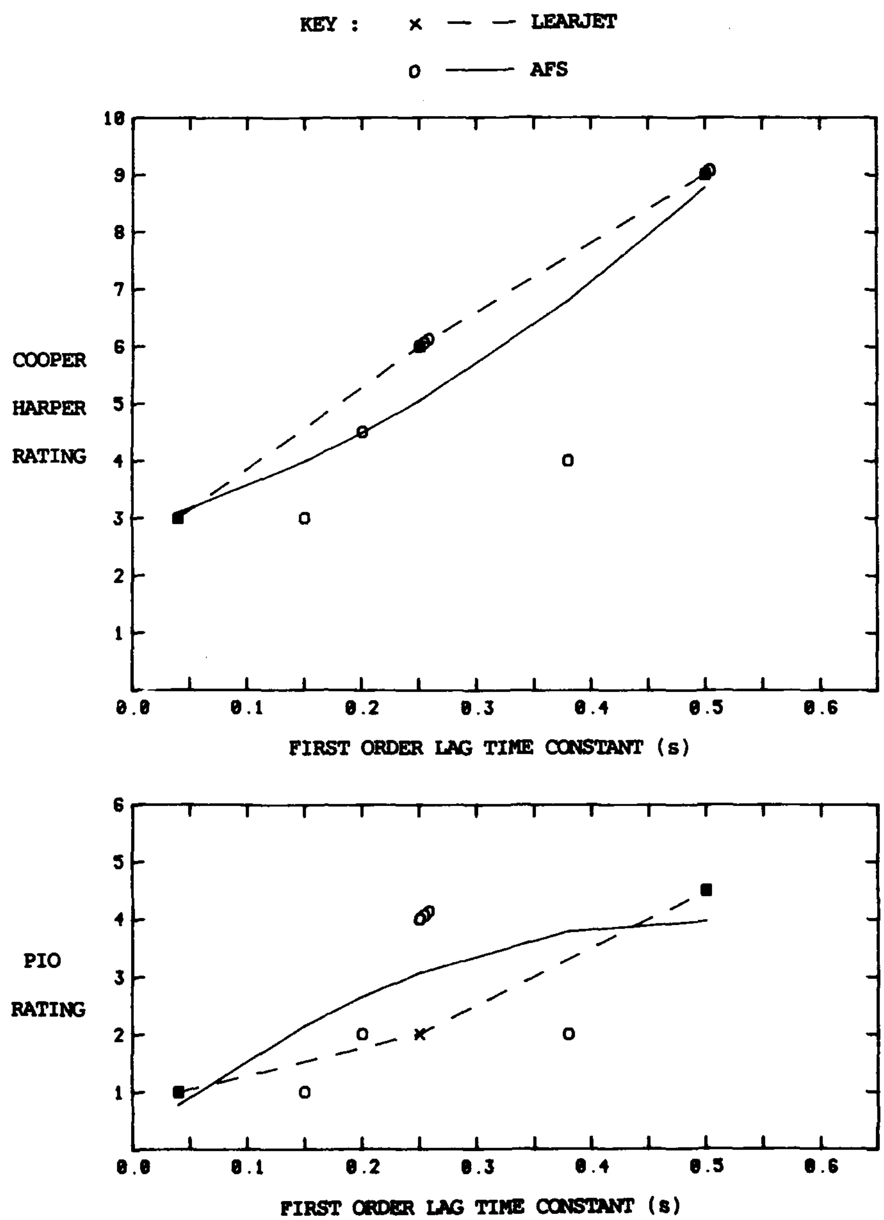


Fig.9 Pilot ratings from the AFS and Learjet for the offset approach task — Pilot B, Sorties 10 and 11
(NB only 3 configurations flown in the Learjet)

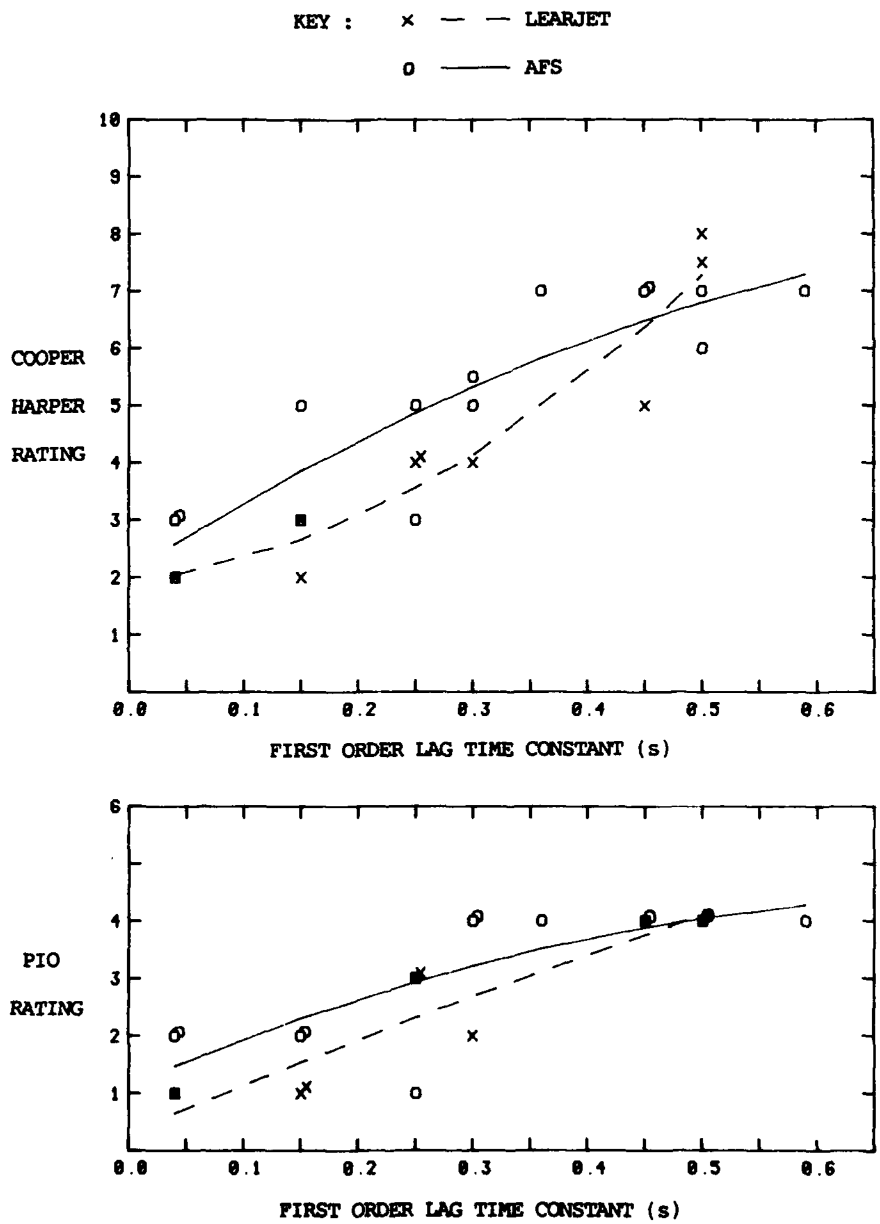


Fig.10 Pilot ratings from the AFS and Learjet for the offset approach task — Pilot C, Sorties 8 and 9

5.2 Factors affecting PIO sensitivity

Concerning the scatter in the results, some factors are common for both simulators such as the different levels of turbulence and crosswind experienced on different sorties. Scatter will also be produced by differences in control 'gain' between pilots, or even for the same pilot under slightly different circumstances. For example, poor handling qualities may not become evident until the pilot is forced to adopt a high-gain closed-loop control strategy. If, through luck or good judgment, his perceived error remains within acceptable bounds he may remain at low gain. The following pilot comments from consecutive approaches with an identical configuration illustrate the point :-

Pilot A — Sortie No 5 (Learjet) — 500ms lag.

Run 6a, CHR 5, PIOR 2

"Small oscillations initiated during final approach. Retains reasonable accuracy. Oscillatory motions start as I attempt to tighten the task. Predictability reduced compared to baseline configuration."

Run 6b, CHR 8, PIOR 4

"Very definite PIO. Would not like to subject a squadron pilot to this aircraft. Very difficult aircraft to control even under the optimum flying conditions of today."

At a filter time constant of 250ms there appears to be a transition from an obviously good configuration, which requires little pilot compensation, to an obviously bad one where pilots are forewarned long before touchdown. Notice the greater scatter in PIO ratings for this value of filter time constant (see Fig 7) compared with lower values. Pilot ratings for these intermediate configurations in particular are likely to be sensitive to differences in perceived track errors at the beginning of the closed-loop phase, ie the roll-out onto the runway centre-line, and in perceived bank errors near touchdown when pilots need to level the wings.

The following comments from Sortie No 6 refer to differences in perception of lateral handling qualities for the same configuration during the roll-out onto the runway centre-line:-

Pilot A — Sortie No 6 (AFS) — 250ms lag.

Run 7, CHR 2½, PIOR 1

"I quite liked that one. Predictability was good and it required only two corrections, one to stop the roll rate and one to correct any error, to line up with the runway centre-line."

Run 12, CHR 5½, PIOR 3

"...I had to adopt a more open-loop control strategy and be less aggressive to achieve the desired task performance. A small PIO was generated and it required four or five lateral concontrol inputs to roll-out and stabilise on the required heading, wings level."

Even if the roll-out has been satisfactory, intermediate configurations have the potential to cause problems near touchdown as pilot gain increases, as shown by another pilot's comments for the same configuration:-

Pilot C — Sortie No 9 (AFS) — 250ms lag.

Run 6a, CHR 5, PIOR 3

"Still taken by surprise that the final adjustments close to touchdown are so difficult and cause some oscillations when the initial recovery to the runway centre-line is so satisfactory. All very similar to the aircraft."

Run 6b, CHR 3, PIOR 1

"A much easier system to fly than the previous one [ie Run 6a]. I had a small offset and therefore the initial inputs were smaller and there was no tendency to generate an oscillatory response. Felt like a different vehicle."

The greater variation in ratings obtained in the AFS may be explained by adaptation effects, differences in task execution and urgency and variations in task initial offset and height.

Adaptation effects showed up as a general trend towards lower pilot ratings with increasing practice and most obviously in repeat runs of the baseline configuration, which were rated better than first runs. One reason for this might be that the straight approaches performed in the AFS did not give pilots sufficient time or opportunity to adapt, compared to the Learjet where they flew a complete circuit with each configuration. For instance, one pilot felt that he could not help learning to adapt to the characteristics of each configuration as he flew the Learjet in the circuit. Further, repeat runs before ratings were given were more common in the Learjet than in the AFS. Taken together this would explain both the larger scatter and the higher average ratings given for the same configuration in the ground-based AFS. Learning effects were most graphically illustrated by Pilot A, who flew an additional AFS sortie (No 7) on the same day as his AFS evaluation sortie. Those results which are directly comparable (ie motion on) show that the trend towards lower ratings with increasing practice which began in Sortie No 6 has continued into Sortie No 7 (Fig 11), confirming that adaptation is taking place. The rapidity with which pilots subconsciously learn to adapt to new configurations emphasises the importance of side-by-side comparisons of ground-based simulators with flight for validation exercises.

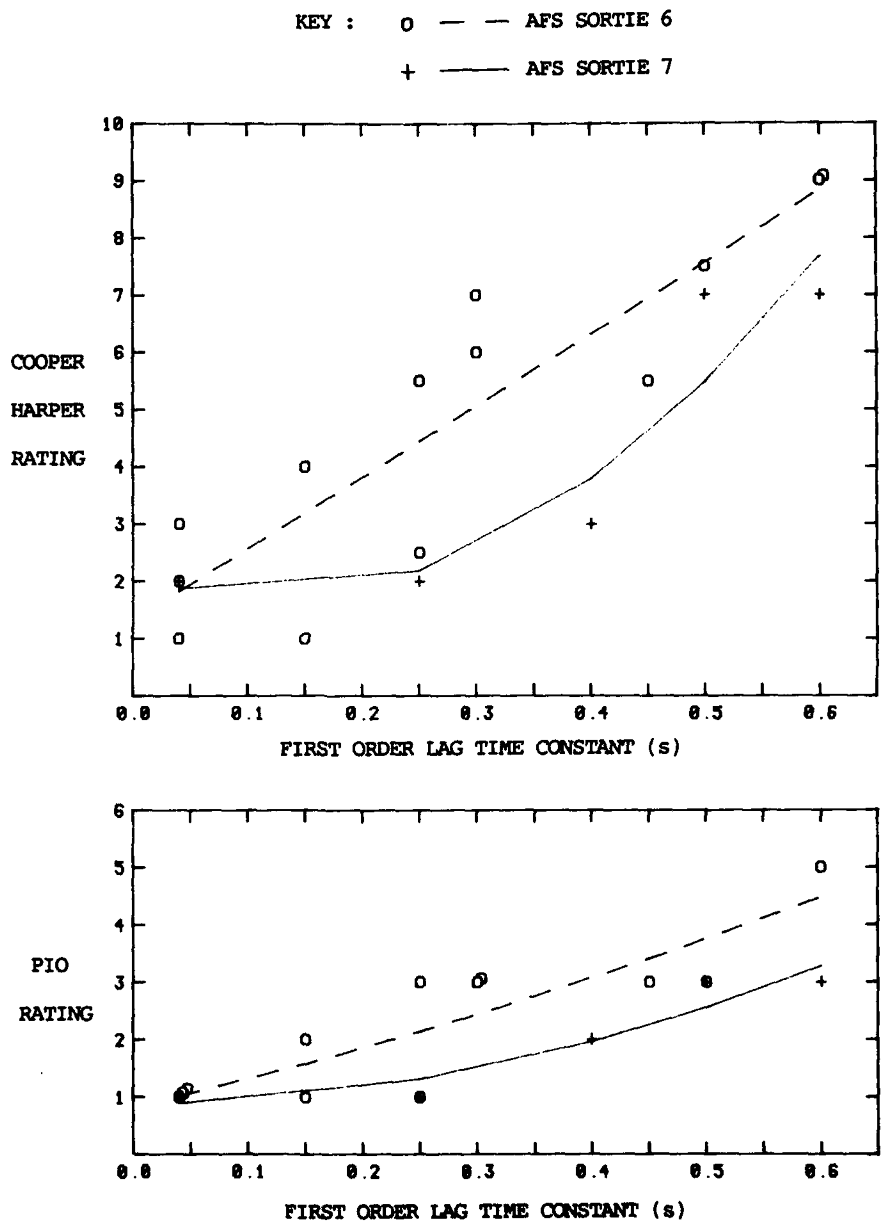


Fig.11 Pilot ratings from the AFS for the offset approach task showing the effects of adaptation — Pilot A, Sorties 6 and 7

A second explanation for the presence of greater adaptation effects in the AFS could be that either the aircraft model or the cueing environment is not the same. Supporting evidence for this comes from pilot comments, which indicate that the initial roll response of the baseline configuration in the AFS was "less brisk" than in the Learjet and that uncommanded side-forces were present in turns. Comparison of the aircraft model implementations must await completion of parameter identification work on the Learjet by Calspan, but at this stage there are no reasons to suspect significant differences. The apparently more docile initial response in the AFS could be due to the attenuation of roll motion (gain = 0.3) and the uncommanded side-force in turns is almost certainly a false motion cue. The false cue manifested itself only during the large amplitude (mainly open-loop) 'S' turn and not during the critical PIO-prone touchdown phase. In fact the AFS reproduced this phase very well, including the ability to surprise pilots in the same way as the in-flight simulator as already noted above in Pilot C's comments from Run 6a, Sortie No 9.

Thirdly, task urgency in the mind of the pilot will always be greater in flight, even with a safety pilot present, than in a ground-based simulator. As a result, a pilot will be encouraged to work at higher gain and hence consistently closer to any cliff edge in the handling qualities or PIO tendencies of the vehicle and this will tend to reduce the scatter in the results. In contrast, the pilot in the ground-based simulator can afford to fly at a lower gain, knowing subconsciously that any failure to control the vehicle will not be terminal, and this will tend to increase the scatter in the results from run to run and sortie to sortie.

Finally, the temporary lack of PAPI lights on the AFS visual system meant that a talk-down procedure had to be adopted instead. This may have introduced greater positional variation, particularly in height, at the start of the 'S' turn than was the case with the Learjet. An examination of recorded data may indicate whether this variation was significant.

5.3 Platform Motion Cueing

In addition to his evaluation sorties, Pilot A flew an additional AFS sortie (No 7) with the objective of identifying the effects of motion cueing on perceived handling qualities. The comparisons were made in motion on/off pairs for each filter time constant. Figure 12 clearly indicates a significant relative degradation in handling qualities when motion cues are absent. Pilot A commented that motion provided him with cues which enabled him to control the vehicle better:-

Pilot A — Sortie No 7 (AFS) — 40ms lag.

Run 1, Motion on, CHR 2, PIOR 1

"A nice predictable crisp response."

Run 2, Fixed-base, CHR 3, PIOR 1

"The lack of motion wher manoeuvring hard gives a strange sensation. The world is moving fast but the semi-circular canals are not stimulated: ie my sensations are not tieing in. I experienced mild vertigo, as happens when people are spun on a chair. The aircraft response was not as crisp and I flew less aggressively and more open-loop. One or two extra control inputs were required to stop the rolling motion."

Time histories (Fig 13) from another approach during the same sortie also show clear differences in control and performance. With motion cueing present, the pilot was able to suppress the oscillation more easily.

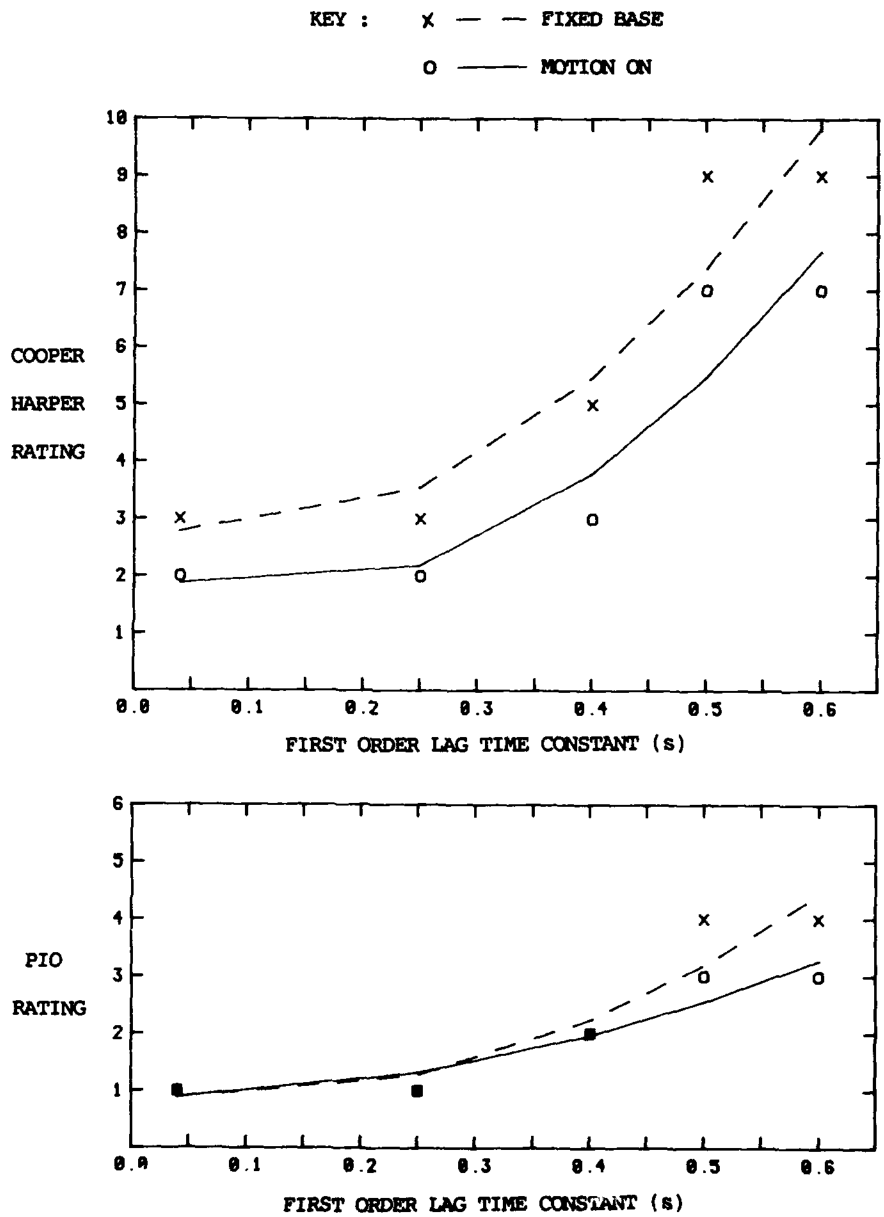


Fig.12 Pilot ratings from the AFS for the offset approach task showing the effects of motion cueing — Pilot A, Sortie 7

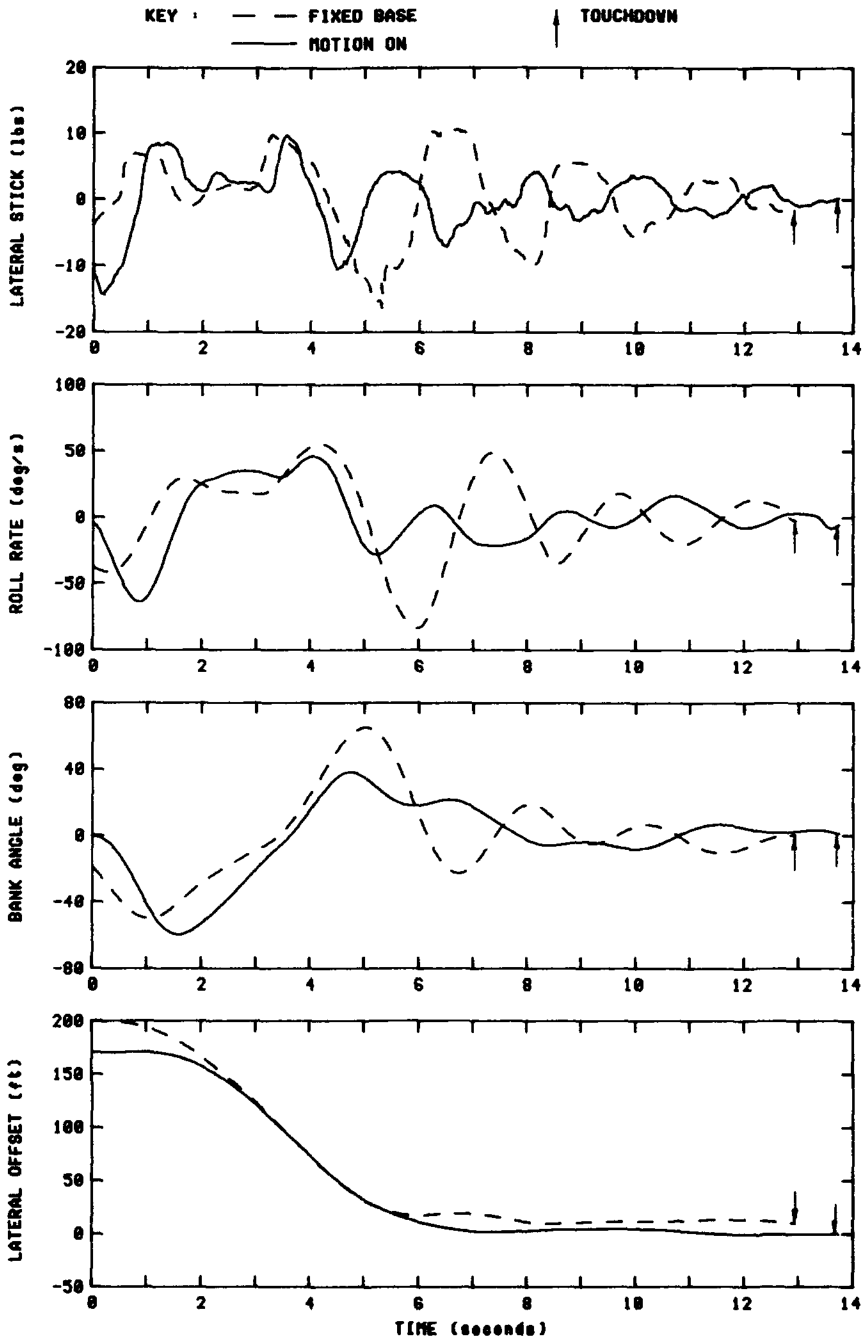


Fig.13 Time histories from the AFS for the offset approach task showing the effects of motion cueing — Pilot A, Sortie 7 (lag 0.4s)

Motion cueing was also found to make the simulation feel more like an aircraft in the first phase of the trial (Ref 1), which investigated the effects of added time delay on a different vehicle model. In contrast to the second phase, however, the absence of motion cues was found to improve, not degrade, the perceived handling qualities and PIO tendencies of the vehicle. Further, for some pilots the fixed-base simulation predicted only a small increase in PIO tendency with increasing time delay, unlike the flight result, and hence could not be used to predict PIO tendencies with any confidence. Pilots commented that motion enabled them to pick up cues which told them how bad a particular configuration was. They instinctively reacted to these cues to compensate for the perceived deficiencies of the configuration and this tended to make them drive the PIO. All pilots felt that flying was much more realistic with motion cueing, as in the following example:-

Pilot 1* — AFS Workup Sortie No 1 — *140ms added time delay

Run 2. Motion on, CHR 7, PIOR 4

"Significant time delay. Definite PIO tendency — had to reduce gain. Large aggressive inputs required, especially close to the ground and worst late in the flare. Full stick to hold 15 degrees of bank close to the ground — close to scraping a wing."

Run 3, Fixed-base, CHR 4, PIOR 2

"Just steering the visual displays. No sensation of rolling and yawing — nothing driving the PIO. With motion ON you feel the accelerations and this drives you subconsciously to drive a PIO. Motion OFF is easier, but more like a video game."

Here again time histories support pilot comments as shown for another approach, with 180ms added time delay, from the same sortie (Fig 14). The pilot has used motion cues to increase his operating frequency and has induced a lateral PIO near touchdown.

Unfortunately, differences in vehicle models, use of time delays instead of time constants and many other experimental factors prevented the cause of these fundamental differences being identified. However, it is likely that motion cueing encourages pilots to close the control loop more tightly and aggressively, ie at higher frequency and gain. In some circumstances this may improve handling and performance by increasing the perceived bandwidth of the system whilst in others it may cause a degradation by inducing over-control. Note that operation at a higher frequency is more likely to cause handling difficulties for the added delay case since there is no attenuation with increasing frequency and phase lag increases more rapidly than for a first order filter. Further work is necessary to resolve this issue.

5.4 Task Design

The fact that some aircraft have exhibited a handling deficiency only when facing a new task (eg space shuttle) or very late in their development programme (Tornado heavy landing) illustrates the importance of task design when evaluating handling qualities. A demanding task is required to keep the pilot operating at high gain and closed loop and thereby to encourage him to find any cliff edge in the handling qualities or PIO tendencies of the vehicle.

In-flight simulation has the advantage of maintaining task urgency (as discussed in Section 5.2) but safety considerations limit how demanding the task may be made. The ground-based simulator has the advantage that the task may be made increasingly demanding in order to find any cliff edge and to determine whether it could ever occur within the vehicle's operational flight envelope.

The difficulty with the task used in the Learjet/AFS trial is that one or two control inputs early in the approach are sufficient to tell the pilot how poor a given configuration is likely to be on finals. For poor configurations, a pilot's natural inclination is to be less aggressive in the 'S' turn and to use a lower gain, and indeed many pilot comments referred to a reduction in gain or adoption of a more open-loop control strategy. Only in the brief period immediately prior to touchdown, when ground proximity forces the pilot to keep the wings level, does he have to use high-gain closed-loop control. This leaves little time for PIOs to develop.

One variation in task design considered in the first phase of the trial (Ref 1) was to give the pilot the baseline vehicle for the approach task, brief him to fly it aggressively and to add the time delay during the 'S' turn to recover to the runway centre-line. It is argued that this task is more representative of aircraft which exhibit a PIO tendency only after hitting some form of system non-linearity (eg actuator rate or acceleration limits) during a high gain task. In this way the pilot is calibrated to fly a good configuration and is therefore operating at a consistently high gain regardless of configuration. Rating consistency was much improved using this technique and it will probably be used in future work.

Where the above technique is inappropriate, eg when evaluating control laws, an alternative approach is required. One technique is to increase the time spent in close proximity to the ground by signalling pilots just prior to touchdown to land farther along the runway (Ref 7).

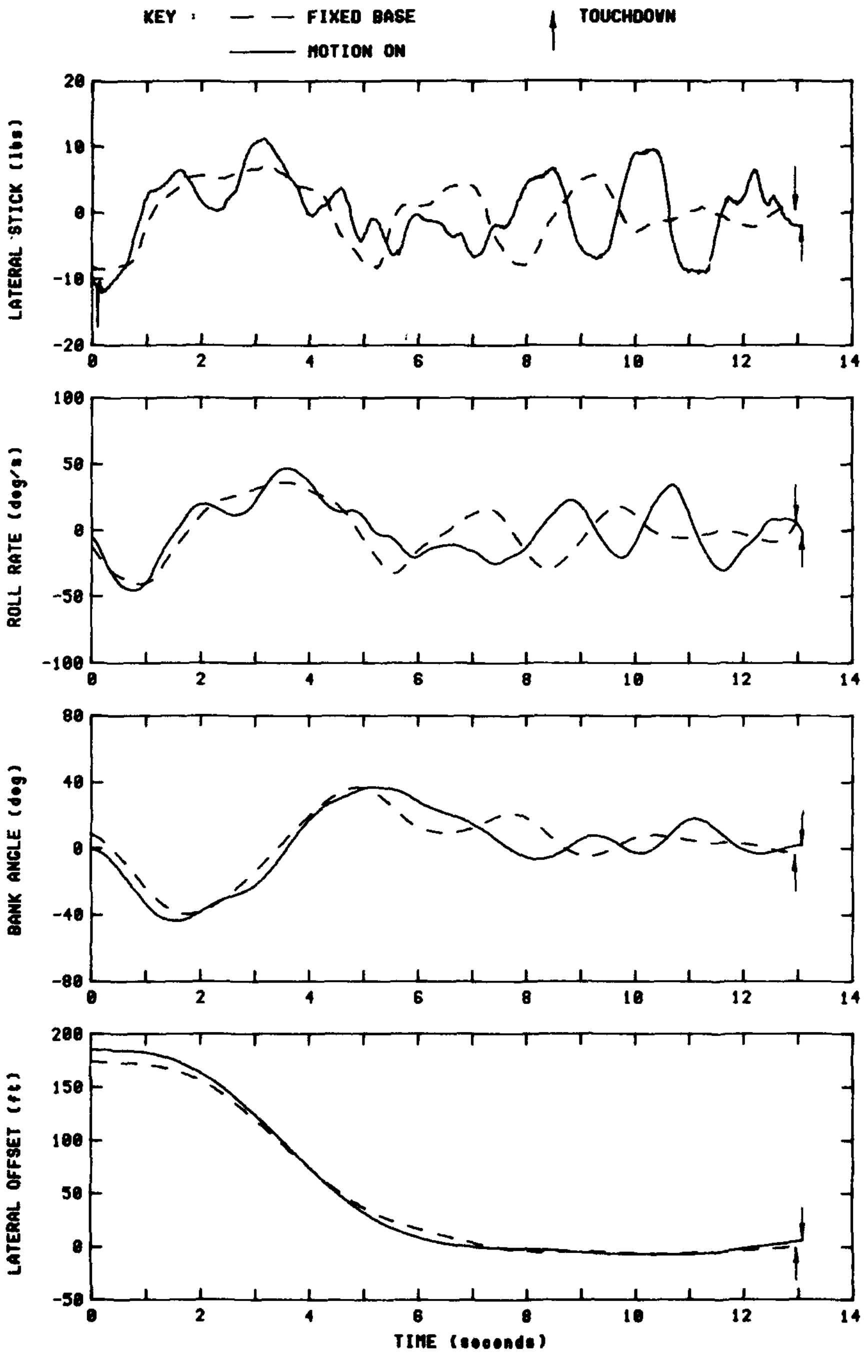


Fig.14 Time histories from the AFS for the offset approach task showing the effects of motion cueing — Pilot 1, Workup sortie 1 (added delay 180ms)

6. CONCLUSIONS

Comparison with flight has shown that the Bedford Advanced Flight Simulator (AFS) reproduces with a high level of fidelity the lateral flying qualities and PIO tendencies obtained in an offset approach task. Specifically, the degradation in handling qualities and increase in PIO tendencies with increasing control system lag was clearly predicted by both the AFS and the Calspan Learjet in-flight simulator and, on average, the difference in Cooper-Harper and PIO ratings was less than 1 point.

Good platform motion cueing was shown to be essential if handling qualities, and in particular PIO tendencies, are to be reproduced with any confidence in a ground-based simulator. The absence of platform motion could make the simulator easier or more difficult to fly depending on the particular handling characteristics of the vehicle and, in some cases, pilot sensitivity to changes in handling qualities was greatly reduced. Handling quality evaluations from a simulator without good platform motion cueing cannot thus be assumed to be consistently either pessimistic or optimistic.

The trial emphasised the importance of side-by-side comparisons of ground-based simulators with flight for validation exercises because of the rapidity with which pilots subconsciously learn to adapt to new configurations. It also demonstrated the importance of task design when evaluating handling qualities and PIO tendencies.

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USE OF A VIRTUAL COCKPIT FOR THE DEVELOPMENT OF A FUTURE TRANSPORT AIRCRAFT

by

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SUMMARY

This paper describes a development tool called "Virtual Cockpit" which is used at Deutsche Airbus.

The following aspects are discussed :

- A comparison of civil and military transport aircraft developments shows a significant technology gap on the military tactical transport side during the last 30 years. Therefore, it seems very beneficial to consider a "dual use" of well-proven "civil technologies" for military applications.
- Specific military transport missions require aircraft capabilities, some of which are quite new and therefore challenging for transport aircraft (e.g. low-level flight profiles in night and poor-visibility conditions). The demonstration of the feasibility and an evaluation of technical solutions imply the need for suitable development tools.
- The Virtual Cockpit is explained in terms of its components (hardware/software), features and capabilities. A major field of investigation in this context is the aircraft systems' central control and monitoring.

1. COMPARISON OF CIVIL AND MILITARY TRANSPORT AIRCRAFT DEVELOPMENTS

1.1 Technology gap in Military Transport Aircraft Developments

The airforces of the NATO partners mainly use C-130 HERCULES and C-160 TRANSALL aircraft for their tactical/logistic air transport tasks. These aircraft have been developed during the end of the 50's or the beginning of the 60's. They are reaching the end of their life cycles and - due to their old technologies - are increasingly causing problems in all fields of operation and maintenance. That is why different partners have started upgrade programmes, which will permit to keep these aircraft in operation until about the year 2000.

In the civil air transport world there has been a continuity of aircraft development and production, which resulted in an evolution of three aircraft generations, during the same time frame.

The "technology gap" in tactical transport aircraft developments is shown in fig. 1.

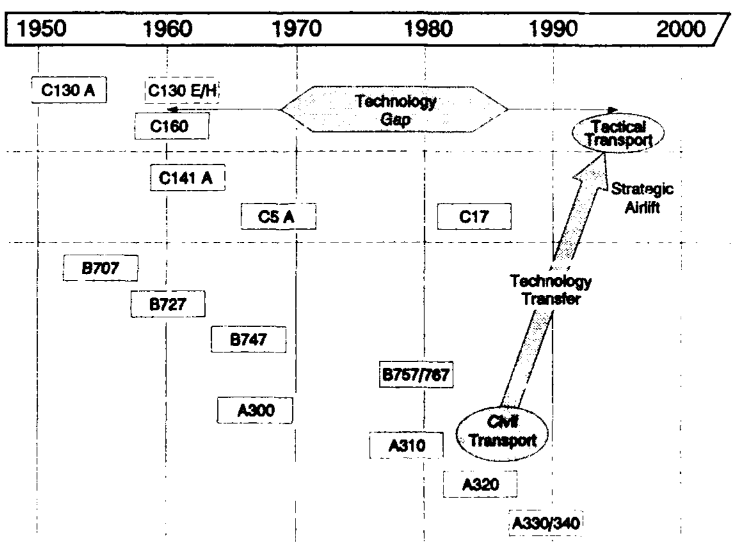

Fig. 1: Comparison of Civil and Military Transport Aircraft Developments

1.2 High Lights of Cockpit Evolution Demonstrated on the Basis of AIRBUS Products

The avionics of the first European wide-body aircraft, the AIRBUS A300, as well as of all the other aircraft of the early 70's still depends on analog-technology equipment. Systems have to be controlled by means of dedicated switches and knobs, and system information is provided via numerous electro-mechanical indicators. The aircraft operation requires a 3-member crew (captain, first officer and flight engineer), whom the cockpit is designed and furnished for (fig. 2).

The general application of digital avionics equipment and the introduction of computer-controlled systems as, for instance :

- Flight Management System (FMS)
- Electronic Flight Instrument System (EFIS)
- Electronic Centralized Aircraft Monitor (ECAM)

leads to a higher level of automation. As a consequence this permits to reduce the cockpit crew to two members in the second generation, for which the AIRBUS A310 is a well-known example (fig. 3).

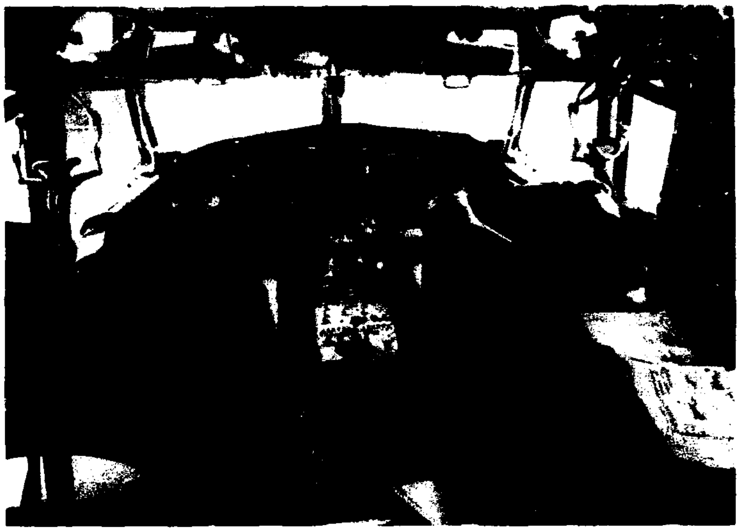

Fig. 2: 3-Crew Cockpit of a BOEING B727

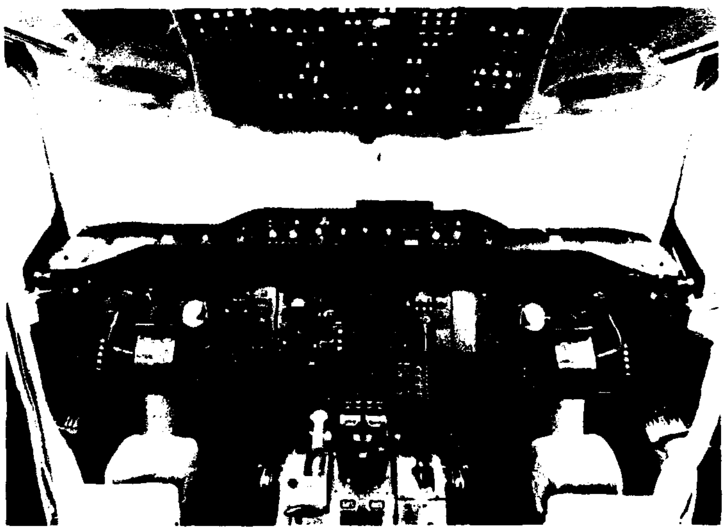

Fig. 3: Cockpit of an AIRBUS A310

Flight guidance and navigation information as well as system data are presented on multi-function CRT's (Cathode Ray Tubes), while engine parameters are still indicated on conventional instruments. Mechanical switches on the overhead panel are substituted by integrated push buttons ("Lights-Out" philosophy).

With the third AIRBUS generation A320 the "fly-by-wire" technology is introduced. The conventional control columns are replaced by side stick controllers, which permit an unobstructed view over the main instrument panels, where the Primary Flight Displays (PFD's) and the Navigation Displays (ND's) are located side by side. The engines are also controlled electronically by FADEC's (Full Autority Digital Engine Controllers). Engine parameters are also presented on a CRT (Engine /Warning Display). Only the stand-by instrumentation is still conventional (fig. 4).

1.3 "Dual Use" of Well-Proven "Civil Technologies"

Together with several other European aircraft manufacturers Deutsche Airbus has started the work related to the design of a new military transport aircraft called "FLA" (Future Large Aircraft). Taking into account the situation of the "technology gap" (as explained earlier) on one side, and being aware of the time constraints for the different project phases until service entry ("technology readiness") and also the financial volume of a new aircraft development, it seems very beneficial to consider a "dual use" of well-proven "civil technologies" for military applications. Areas for a possible technology transfer on the avionics sector will be :

- Flight control/flight guidance
- Flight management
- Displays
- Centralized aircraft monitoring
- Application of modular avionics architectures

2. REQUIREMENTS FOR A NEW MILITARY TRANSPORT AIRCRAFT

Specific military transport missions require aircraft capabilities, which are well beyond civil applications. These requirements represent the dimensioning factors for the overall design as well as for the mission equipment. Some of these requirements, which refer to cockpit and avionics design are:

- Low-level flight (Terrain Following, Terrain/Threat Avoidance)
- Operation in night and bad-visibility conditions
- Bord-autonomous precision navigation and landing
- Onboard mission planning
- Para-dropping
- Communication with ground-based and airborne command and control systems

etc..

These operational requirements, some of which are quite new for transport aircraft capabilities (and therefore quite challenging), have to be met by concepts of technical solutions.

The demonstration of the feasibility of new technologies and an evaluation of the design concepts imply the need for suitable development tools especially in order to investigate Man-Machine-Interface (MMI) aspects and cockpit-related tasks.

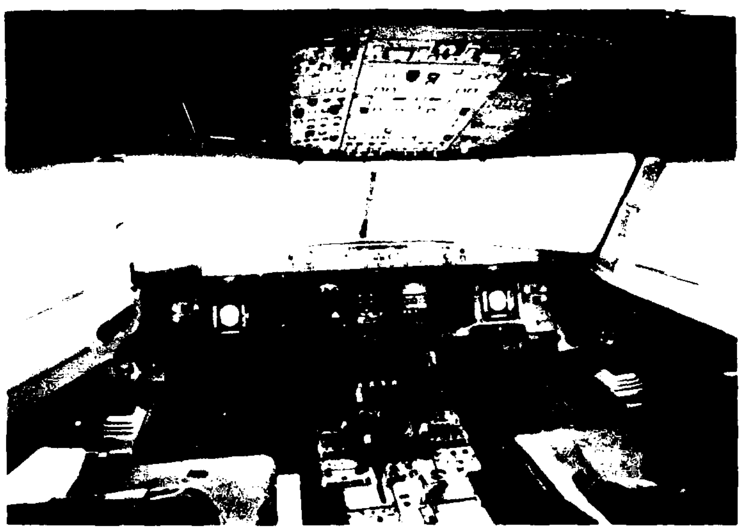

Fig. 4: Cockpit of an AIRBUS A320

3. DEVELOPMENT TOOLS FOR THE INVESTIGATION OF COCKPIT-RELATED TASKS

The feasibility and pre-development phase of a product like a transport aircraft is of great significance because, during this phase, all the performance and configuration characteristics will be defined, which will influence about 85% of the product's life cycle cost (LCC), whereas only less than 10% of LCC have been spent (fig. 5).

"Cockpit" is the synonym for numerous requirements originating from the various disciplines and their specific view points involved in the pre-development process, e.g.: aerodynamic and structural design, system design, ergonomic design, industrial design etc..

The development tools which are suitable for the assistance and support of the different disciplines are of great variety, of course, ranging from computer-aided design tools via engineering mockups up to full-scale flight simulators. Their applications are always a compromise between the kind or depth of investigation and the required - or better - the justified effort. As the technical goals of the pre-development phase and the corresponding main tasks we consider :

- Validation of operational requirements
- Demonstration of the feasibility of concepts
- Evaluation of applicable technologies
- Identification of risks w.r.t. technology readiness
- Assessment of user acceptance

As members of the department "Pre-Development Cockpit and Avionics" at Deutsche Airbus we have installed a development tool called "Virtual Cockpit" which supports us in solving our MMI-related tasks.

4. "VIRTUAL COCKPIT"

The leading idea of the "Virtual Cockpit" is to use

SOFTWARE instead of HARDWARE

This means to use modern input and ouput devices on the latest generation computers instead of cutting metal and soldering wires. So the "Virtual Cockpit" provides a comfortable tool to check out the MMI of the cockpit long before the real components are available.

4.1 Components

The computing task is distributed on several RISC workstations, where each processor has its specific task. The workstations are linked by ethernet (fig. 6). The overall computing power is adjustable to the needs of the application by the number of workstations. At the moment only workstations of one architecture are used. But the application of industry standards makes it possible to connect heterogeneous hardware platforms.

The cockpit controls and indicators are displayed on several graphical colour monitors (fig. 7). All these monitors are equipped with touch-sensitive overlays to provide direct activation of push buttons, knobs, switches and so on.

The output of voice and sound - warning tones for instance - is provided by the internal audio device of the workstation. The geometrical arrangement and the size of the simulated controls and indicators on the monitors matches with the original. To allow undisturbed studies the relevant devices are installed in a rig construction, wich is housed in a cabin. The rig construction offers a good flexibility w.r.t. modifications and extensions of the arrangement (fig. 8).

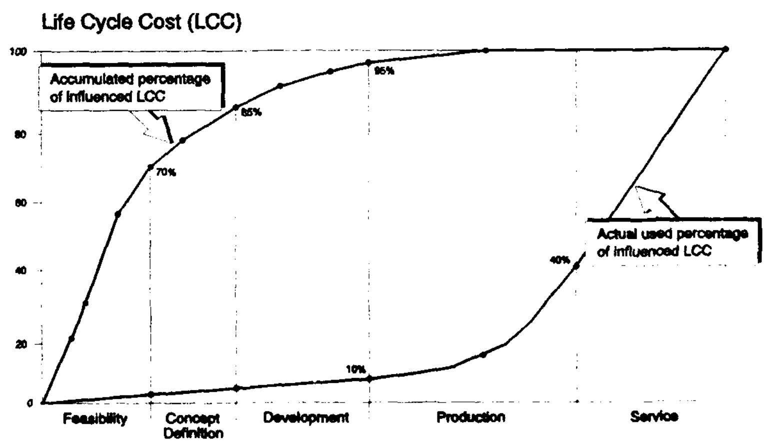

Fig. 5: Susceptibility of Product Cost Within the Life Cycle

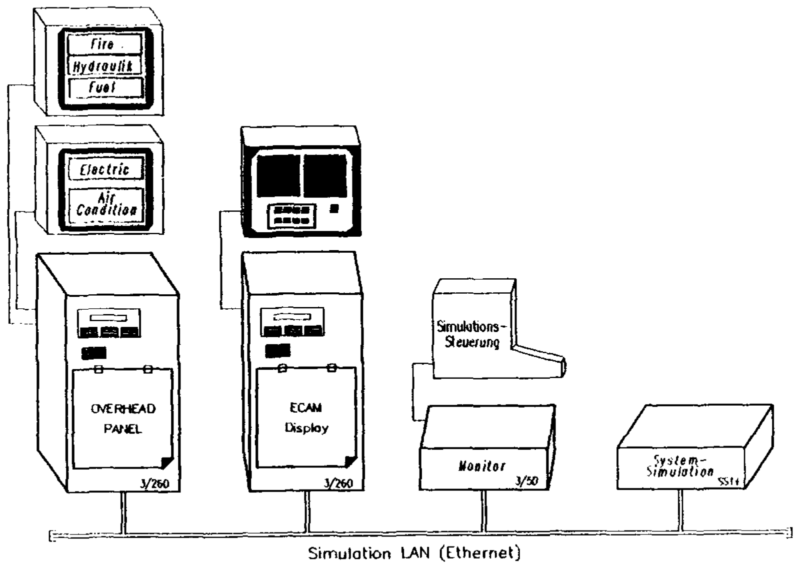

Fig. 6: "Virtual Cockpit" Computing Network

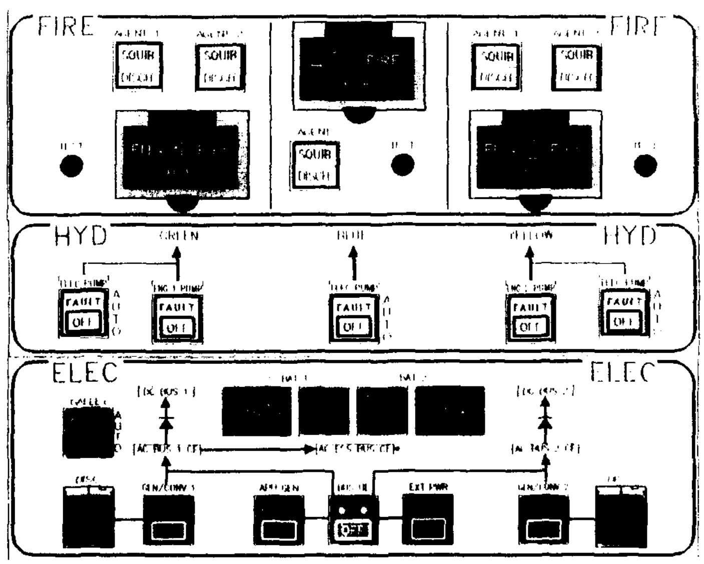

Fig. 7: Simulated System Control Panels

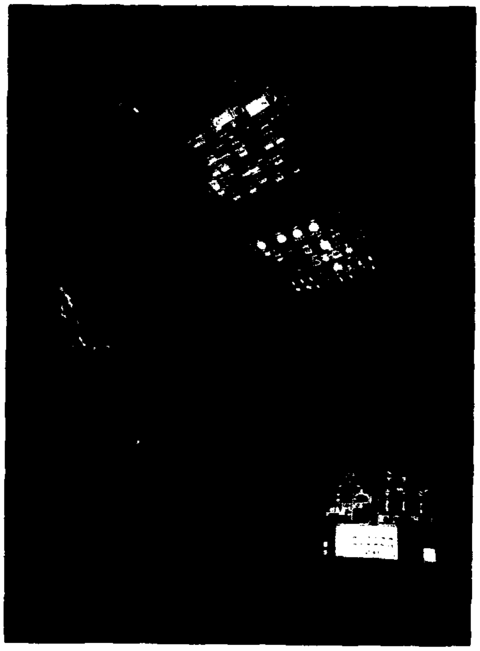

Fig. 8: "Virtual Cockpit" Cabin

4.2 Features

The "Virtual Cockpit" is a flexible and versatile tool to examine several aspects of cockpit development, e.g.

- Development of display formats
- Design of the control panel layout
- Development and test of monitoring algorithms
- Dynamic simulation of man-machine-interactions
- Examination of the controllability of aircraft systems (what and how many knobs do I need?)
- First assessments of pilot workload
- Development of abnormal and emergency procedures including alarms, switching pattern and the usage of electronic checklists
- Provision of colour plots of displays and control panels for the construction of full size cockpit mock up's

4.3 Present Applications

To ease the pilots' tasks the various systems of modern transport aircraft (like AIRBUS A340) are supervised by an electronic monitoring system for instance the ECAM (AIRBUS) or EICAS (BOEING). Because the control algorithms depend on the specific system architecture of the aircraft, the monitoring system and its software is unique to each aircraft type. The algorithms are based on fault analysis and failure propagation studies of the aircraft system. Unfortunately they can be determined rather late in the development process because the systems have to be defined in detail, before. In the pre-development phase of the Deutsche Airbus project MPC75 the "Virtual Cockpit" is used as a rapid prototyping means to investigate the requirements of the monitoring system itself, its interfaces to the linked systems and the information presentation to the cockpit crew.

This application includes all the functions necessary for the aircraft systems control and monitoring (fig. 9). Several aircraft utility systems, like engines, hydraulic and electric power, fuel, environmental control, are numerically simulated. They are controlled via the overhead panel. The simulation control interface provides the stimulation by introducing component failures.

The simulated components of the monitoring system are:

- Failure identification and diagnostic systems with
  - Flight warning logic
  - Flight phase computation and
  - Warning management logic
- Control panel
- Attention getter with
  - Master light
  - Acoustic warning
- Display system with
  - Display management logic
  - Engine and warning display
  - System and status display

4.4 Further Fields of Investigation

A logical extension of the "need-to-know" principle, which is applied to present aircraft generations (e.g. AIRBUS A320), to a "need-to-control" principle leads to the following conceptual approach of a aircraft systems centralized control (fig. 10).

This approach attempts to integrate all control and display elements related to the aircraft candidate systems concerned into one single device consisting of a display with a touch-sensitive overlay. The activated control input area is an integral element of the display format presented to the pilot. Thus, both the information for the required actions and the corresponding control elements will be provided only when necessary.

The concept of centralized aircraft systems control seems very promising for military transport aircraft applications, especially when considering a two-crew operation. Potential aircraft system candidates for a centralized control are, for instance :

- Aircraft utility systems (electric power, hydraulic power, air conditioning system etc.).
- Flight management/mission management system.

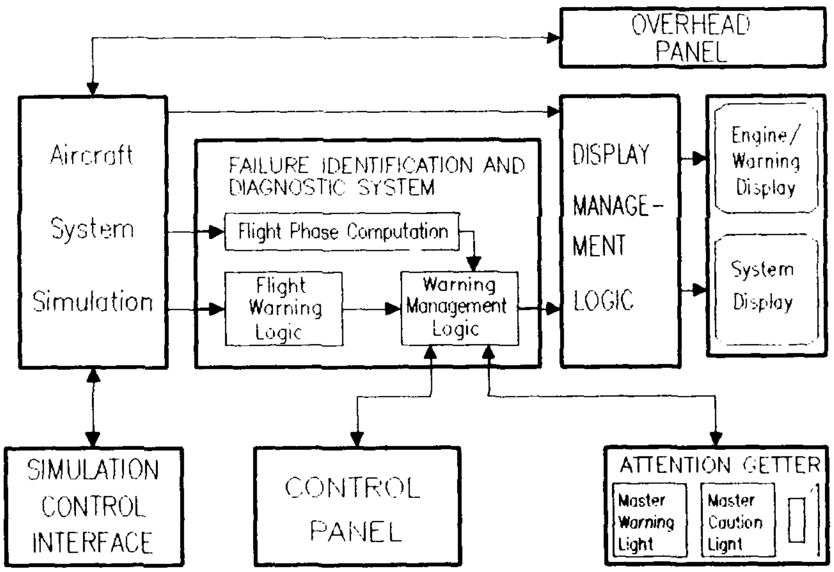

Fig. 9: Functional Block Diagram: Aircraft System Control And Monitoring

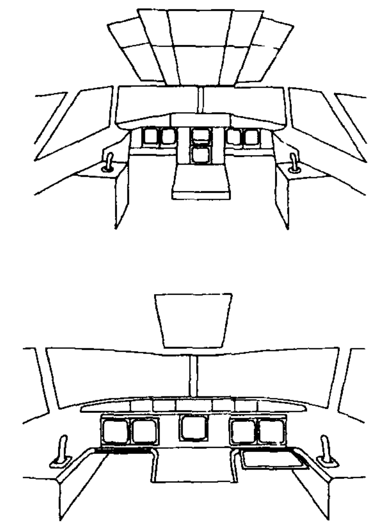

Fig. 10: Concept of Aircraft Systems Centralized Control

4.4.1 Aircraft Utility Systems Operation

During normal operation most of the aircraft utility systems work automatically (exception : required actions related to the cockpit preparation procedure). Only in cases of failures manual system reconfigurations become necessary. The corresponding actions are part of directed procedures written on paper check lists or presented on the ECAM displays. Most actions to be taken are discrete switchings, which have to be performed on the overhead panel. In cases of multiple system failures the procedures can become quite complex. In such situations, it would be very beneficial to have the system control elements and the corresponding information media for the required actions as well as for the system feedback of performed actions at the same local place.

4.4.2 Flight Management/Mission Management System

1. Flight Management System (FMS)

The FMS integrates two major functions :

- Performance management
- Navigation management

The output data, i.e. advanced flight guidance data serve as input data for the Auto Flight System (AFS) and are provided for the EFIS displays.
Despite the fact that the FMS uses inputs from almost all other avionics equipment on board, still many data have to be entered manually by the pilots via the Multi-Purpose Control and Display Unit (MCDU), which is not satisfactory, of course, not only because of the mis-fit between alpha-numeric input a d mainly graphical output on different devices (MCDU and EFIS) at different physical locations.

2. Mission Management System (MMS)

A military Mission Management System (for transport aircraft) can be considered as an "add-on" to the civil Flight Management System providing three main functions :

- Information gathering
- Information processing
- Information distribution

For this purpose the MMS communicates with the specific military mission equipment on one side and represents the interface to the "civil part" of the avionics on the other side, as indicated in fig. 11.

So, the user side of the Mission Management System is a good example for a centralized aircraft systems control.

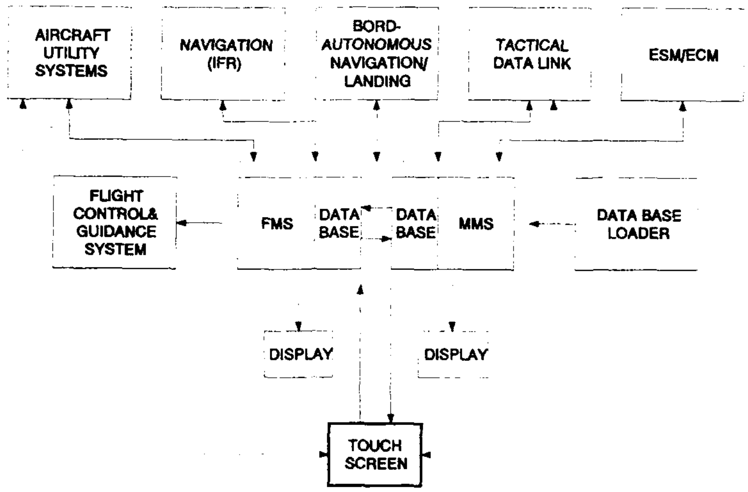

Fig. 11: **Functional Block Diagram of the Flight Management / Mission Management System**

5. *CONCLUSIONS*

In the previous chapter we have described our development tool called "Virtual Cockpit" in terms of components, functions and its application of a centralized aircraft systems monitoring and control concept. At the end, we would like to highlight the benefits of this tool we have experienced so far.

The development process of a new concept of centralized aircraft systems control includes the following main steps:

- Investigation of aircraft candidate systems to be controlled centrally (e.g. utility systems, FMS, MMS, etc.)
- Investigation of suitable control input devices (e.g. touch screen) and complementary devices, as, for instance, voice control (DVI)
- Definition of the control logic
- Definition of the requirements for the touch screen device in terms of
    - Functions
    - Physical characteristics
    - Performance criteria
- Investigation of ergonomic aspects
- Investigation of safety and redundancy aspects
- Investigation of cockpit-integration aspects

The concept evaluation, during this phase, concentrates on the following main criteria :

- Control logic
- Ergonomic aspects
- Physical aspects
- Pilot's task interactions

1. Control Logic

   The evaluation of the control logic can be performed on stand-alone basis. It requires the simulation of the related systems' responses like reactions to control inputs, messages, advisories and warnings in cases of malfunctions.

2. Ergonomic Aspects

   The evaluation of ergonomic aspects like the locations of the touch screens, arm rests, formats of graphical information presentation and visual feedback can also be performed stand-alone. However, some evaluation items require a more "sophisticated" cockpit environment. The investigation of acoustic feed-backs requires the consideration of the noise spectrum inside the cockpit, for instance.

   Other investigation items, e.g. touch field sizes, touch pressure threshold, mechanism of function initiation require the motion of a flight simulator.

3. Physical Aspects

The investigation of the physical aspects of the control device, e.g. display resolution, touch overlay resolution, applicable touch-overlay technologies can also be performed stand-alone.

4. Pilot's Task Interactions

After a successful investigation of all aspects related to the evaluation criteria described before, the influences of concurrent and competing pilot's tasks like ATC communication, navigation etc. will be investigated. These investigations will be subject to an operational flight simulator environment.

The following table shows the applicability of the "Virtual Cockpit" and its features for the development and evaluation process of a new system concept.

EVALUATION ITEMS	EVALUATION ENVIRONMENT		
	"Virtual Cockpit"		Flight Simulator
	Stand-Alone Mockup	System Simulation	
Control Logic			
• System Levels	X	X	
• Information Structure	X	X	
• Control Options	X	X	
• Control Procedures	X	X	
• Priorization	X	X	
• Functions (Skip, Clear, Cancel)	X	X	
Ergonomic Aspects			
• Location	X		
• Arm-Rest	X		
• Size of Touch Fields			(Motion)
• Acoustic Feedbacks			(Noise)
• Visual Feedbacks	X		
• Touch Pressure	X		(Motion)
• Function Initiation (Touch and Lift)	X		(Motion)
• Graphical Presentation (Form, Colors, Legends, ...)	X		
Physical Aspects			
• Display Resolution	X		
• Touch Overlay Resolution	X		
• Parallel Touches	X		
• Applicable Touch Overlay Technologies	X		
• Dimensions	X		
• Performance	X		
Pilot's Task Interaction			X

The investigations described in chapter 4 of this paper have been performed within the context of technology studies, wich are partially sponsored by the German Ministry of Research and Technology and within "FANSTIC" (Future ATC, New Systems and Technologies Impacts on Cockpit), one of the BRITE / EURAM projects sponsored by the Council of the European Community.

The Role of Systems Simulation for the Development and Qualification of ATTAS

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SUMMARY

The Advanced Technologies Testing Aircraft System, ATTAS, is DLR's primary flight test vehicle to be used as a flying simulator to demonstrate and validate new methods and technologies. In order to provide broad testing capabilities ATTAS was heavily modified and equipped with a powerful digital fly-by-wire/light flight control system. Due to system complexity a piloted systems simulator of ATTAS was a critical element for fly-by-wire flight control development and functional validation as well as for aircraft operation. This paper will present a technical description of the simulator structure and simulation capabilities and will adress the specific role of system identification techniques for simulator validation. Several examples will be given demonstrating the performance in system modelling and simulation fidelity by using these techniques. Finally, conclusions concerning the merits of systems simulation for the ATTAS development and operation will be discussed.

1. INTRODUCTION

The Advanced Technologies Testing Aircraft System (ATTAS), (Fig. 1) was developed by DLR and MBB, Bremen, in a project running from 1982 to 1986. Further improvements were continously implemented due to additional requirements. At present the VFW 614 based airplane is DLR's primary flight test vehicle to be used to demonstrate and validate new methods and technologies in the area of highly augmented flight control, flight guidance and navigation, man-machine interfacing and in-flight simulation.

Within DLR's research programs ATTAS will mainly be used as a flying simulator [1,2,3] in a broad sense. In this role ATTAS is able to represent the dynamic behaviour of onboard programmed model aircraft or systems providing exact visual and motion cues to the pilot under real environmental conditions. To provide all these capabilities ATTAS was modified and equipped with a powerful digital fly-by-wire/light flight control system [4,5] designed by DLR. Due to systems complexity piloted and systems simulation of ATTAS was an integral part of the total ATTAS system from the beginning of the project. The ground based piloted and systems simulator of ATTAS was regarded as a critical element for fly-by-wire flight control development (hard- and software) and for functional validation. Additionally, piloted and systems simulation of ATTAS was also planned from the beginning to play an important role during the operational phase to improve reliability, availability and flexibility for research programs.

This paper presents the manner in which the ATTAS simulations were developed to provide the required functions and fidelity, its use during the development phase, and as a result an assessment of its value for development and operation.

2. AIRCRAFT DESCRIPTION

A brief description of ATTAS should help in understanding the complexities of the simulation system and the simulation requirements.

In order to fulfil the research objectives ATTAS was equipped with a complete FBW-system which acts in parallel to the mechanical hydraulical control system of the basic aircraft. The FBW-system has access to all control surfaces and engines with full authority. FBW-mode operations are possible from left hand seat where the right hand pilot acts as safety pilot. He is able to reconvert to the basic aircraft flight control by switching off the FBW actuator clutches.

The main modifications, test equipment and features are summarized as follows (see fig. 2)

- right hand seat safety pilot with conventional control system,
- left hand seat evaluation pilot with full axis fly-by-wire controls,

- freely programmable flight instruments and CRT- displays, (figure 3),
- fly-by-wire controls/column or sidestick with adjustable force feel system,
- dual channel digital on board computer system with fibre optic data bus providing freely programmable control laws and flying qualities,
- duplex inertial reference and digital air data systems,
- comprehensive on board data acquisition system, recording and PCM-telemetry,
- 15 electro hydraulic self monitored actuators, partly duplex linked by MIL-BUS 1553B to the FBW-system,
- antennas installation provisions,
- dual redundant hydraulic system,
- dual redundant electrical system,
- fly-by-wire motivators for
  - o elevator,
  - o stabilizer,
  - o rudder,
  - o both ailerons (also with symmetrical deflection capability),
  - o both engines,
  - o landing flaps,
  - o six direct lift flaps
- on board operator consoles (four places) and
- nose boom with angle of attack-, side slip angle- and TAS-probe (flight log).

2.1 On Board Computer System

The computer system performance meets the requirements for

- computational cycle time of 25 ms for all functions,
- required redundancy for flights in critical conditions
- airborne equipment and interfacing of aircraft systems (ARINC 429, MIL BUS 1553B, etc.) and
- freely programmable capacities for user applications in a high order programming language (FORTRAN 77).

To meet these requirements the system has been designed as a two channel computer network consisting of four processors in each channel with one common central processor for communications and data recording (figure 4). All on board computers are of MIL-Spec. LORAL/ROLM types (MSE/14 and Hawk/32) which are software compatible to the commercial Data General Eclipse S/140 and MV/6000 series. The 32-bit Hawk/32, serves as 'freely' programmable computer for user applications.

The network in each channel is based on a ring structured serial fibre optical bus system providing actual data rate in each channel of 150 kWord/sec. Network redundancy is used for failure detection by comparing exchanged input and output data.

Overall system software design allow simple integration of experimental functions and additional hardware components.

2.2 Fly-By-Wire Control Functions

The Fly-by-Wire/Light Flight Control System (figure 4) as heart of ATTAS provide all operational functions needed for

- normal fly-by-wire operation (control laws, mode switching),
- interfacing external devices,
- data processing and data recording,
- monitoring and error detection and
- computation of user functions.

Operation of ATTAS is performed in the following three principal modes:

- <u>BASIC-Mode</u>
- <u>FBW-Mode</u> (Fly-By-Wire Mode)
- <u>SIM-Mode</u> (Simulation Mode)

In the <u>BASIC-Mode</u> ATTAS is operated using the basic mechanical controls of the safety pilot on the right hand seat in the cockpit.

In the <u>FBW-Mode</u> the evaluation pilot on the left hand seat has control to the FBW-system by connecting the electro-hydraulic actuators to the basic aircraft control system. Flight operation will be performed either identically to the basic controls (FBW 1:1 function) or in an augmented mode providing a Rate Command Attitude Hold (RCAH) control function.

In the <u>SIM-Mode</u> the aircraft also operates under fly-by-wire control but the functional connection between pilot inputs and actuator commands are given by user defined functions such as it is used for in-flight simulation control laws (IFS) where the evaluation pilot flies an aircraft model built in the computer program. Model following control laws generate commands for all the actuators (motivators) to force the host aircraft to follow the on board computed equations of motion.

An automatic elevator trim system operates the stabilizer in such a way that the aircraft is always in trim condition. In cases where the safety pilot reconverts to the basic control system the resulting column and aircraft transients will be negligible.

Evaluation pilot's displays and instruments are controlled by the FBW-system to represent standard EFIS symbology (FBW-Mode). In the SIM-Mode display representation is freely programmable due to user purposes. Specific functions are included in the FBW software program to provide checkout and preflight check procedures.

3. THE ROLE OF SYSTEM SIMULATION

Due to the experiences we gained from the development and operation of DLR's first in-flight simulator, the HFB HANSA-JET, which was developed in the early 70th and operated until 1983 a piloted systems simulator as an integral part of the total 'ATTAS' system was required. The generalized requirements on this simulator were to provide all equipment and functions for

- development and testing of the operational fly-by-wire-software,
- development and testing of the user's flight software,
- validation and acceptance testing,
- software and hardware maintenance and
- failure effect simulation.

In order to fulfil these requirements a very high degree on similarity between the simulator and the flight test aircraft was necessary.

3.1 Hardware structure

The simulator developed is a fixed base simulator without vision and motion [6]. As it is shown in figure 5 the simulator is structured in mainly five elements

- the cockpit,
- the fly-by-wire computer system,
- the interface computer system,
- the simulation computer system and
- the flight software development system.

The cockpit and its systems are absolutely identical in hard- and software to the aircraft as far as the left hand cockpit side is concerned. Also the flight control computer system is identical to the aircraft. All data which are seen by this system are electrically and connector identical to the aircraft. ATTAS sensor systems data as analog data, digital data, discrete data, ARINC 429 data and MILBus 1553B data are provided by the interface computer system based on VME-Bus Motorola 68020 CPU's. The aircraft behaviour itself is simulated in realtime by the highspeed multiprocessor system AD10 specially designed to fulfil continuous hardware-in-the-loop simulation of complex dynamic systems. Simulation software development and interactive handling of the AD10 is performed with the 'host'-computer VAX 3200.

Real-time data presentation is realized by an interactive graphics system DART which is connected to the VME-Bus interface computer and which serves four high resolution (1240 x 1024) monitors providing display informations, time histories and cross-plots.

An important feature of the ATTAS simulation facility is that the flight software development system based on a Data General MV/20000 is directly linked to the flight control computer hardware by the parallel MCA-Bus which is compatible to the serial fibre optic bus which is used to link the five flight computers.

Due to the ring structure of the fibre optic bus the ring could be expanded very easily so that the on board computer system of ATTAS could be connected to the simulation facility allowing hardware-in-the-loop simulation with real aircraft components. This is done for testing purposes if the aircraft is in the hangar or on the apron (see figure 5). Additionally, the software development system, the interface computer system, the host computer and the mainframe computer of the research center are linked by an Ethernet to allow data transfer for data analysis and data evaluation by using centralized software packages.

This structure allows all software developers and system engineers to validate the software under real-time conditions and allow the experimenters to validate the total flight experiment with the ATTAS aircraft systems and pilot in the loop.

Further, if additional experiment dependent hardware should be flight tested, all interfaces and data are provided within the ground based simulation identically to the real aircraft.

The ATTAS simulation facility enables a complete aircraft independent preparation of flight testing so that experiments can be flown with the aircraft and others could be prepared on the ground at the same time.

3.2 Software structure

The flight software is identical to that used in the aircraft. All fly-by-wire functions and user functions are programmed in a high order language FORTRAN 77 under the ARTS real-time operating system for 16 and 32 bit from ROLM. The frame time of the real-time processes running on the ROLM computers is 25 ms.

The interface computer functions are programmed in the 'C' language using the PDOS realtime operating system.

The AD10 software is programmed with the MPS 10 (Modular Programming System for the AD10) simulation language. MPS10 is

a specific software package for the AD10 containing a lot of simulation language elements, which are required by the Continous System Simulation Language (CSSL) standards as:

- modular programming structure,
- extended continous simulation function library and
- interactive software package.

All MPS10 modules are written in the AD10 macro assembler language considering the special hardware structure of this machine.

In order to account for exact simulation of aircraft and systems multiple framing technique was used. The total frametime for aircraft dynamics is 7 ms and for the actuators 1.4 ms.

3.3 Simulation Functions

Simulated functions realized on the AD10 comprises six degrees of freedom simulation of the aircraft within the whole flight envelope, 13 electro-hydraulic actuators including six separate DLC-flaps, two turbo-fan engines, wind and turbulence and the standard atmosphere model.

Aerodynamic coefficients are calculated by linear interpolation with function table look up methods. Within the whole simulation

62 state variables and
413 algebraic variables are used

and the number of data tables as a function of

one variable are 130,
of two variables are 107 and
of three variables are 33.

The VME-BUS interface computer simulates sensor systems like IRS, DADC, VOR, DME, ILS stations and provides correct ARINC 429 data as well as MIL-BUS 1553B data of the electrohydraulic actuator electronic units.

On the host computer VAX 3200 software development for the AD10 is performed as well as all interactive control of the simulation including the interactive process of trim calculations.

3.4 Flight Software Development Environment

The flight control computer as an hardware-in-the-loop element of the simulator is directly connected to a powerful software development system based on a Data General MV/20000 computer. The multi user operating system AOS/VS on the MV/20000 provides the tools for software development and software handling like automatic configuration control and software managing.

In order to achieve a total configuration management system an ATTAS software pool (ASP) was developed containing all validated software modules and allowing to build the required program configurations.

The flight software could be transferred over the parallel MCA bus in the various flight control computers for testing the real-time simulation process.

4. SIMULATION VALIDATION

In order to reach high simulation fidelity and to improve the validation process advanced methods of system identification methods developed at DLR [7,8,9] have been applied for ATTAS simulation.

The method of system identification provide adequate tools to generate reliable and accurate mathematical models and parameters (aerodynamic or system data) with the required fidelity. These data are used to improve and update the simulation data based on windtunnel measurements and theoretical predictions.

Because within the system identification process mathematical model parameters are automatically optimized by minimizing the difference between aircraft flight measurements and model response for a given level of accuracy the validation is provided simultaneously (fig. 6).

The remaining work is to verify that validated model and data (as the reference) are correctly implemented into the real-time program of the simulator. In that case where the required fidelity could not be achieved the mathematical model will be changed or extended until the physical phenomena is described. This method was extensively used for ATTAS aerodynamic data base improvements as well as for actuator and sensor dynamics modelling.

4.1 Aircraft Modelling and Simulation Fidelity Results

To give an impression of the simulation fidelity which could be obtained by this method the following examples are used.

For both, the parameter identification process and for validation ATTAS was excited in-flight by computer generated step sequences in all axis and by all motivators at different flight conditions (flap, speed).

The data of the manoeuvres 1 to 12 as shown in figure 7 have been combined to a total data set for the identification and validation process.

Figure 8 shows the comparison of the flight measured and simulated aircraft response demonstrating that all response variables are perfectly matched by the

estimated parameters. Manoeuvre 12 e.g. was optimized to extract $c_{L\dot{\alpha}}$ -derivatives by banking the aircraft up ± 60 degrees and exciting it in the pitch axis with high frequency step sequences (3-2-1-1 input).

The high accuracy of modelling and response matching should also be demonstrated on the short term pitch response due to DLC-flap deflection considering downwash effects of the flaps on the horizontal tail. As it is illustrated in figure 9 a perfect coincidence between simulation and flight data is obtained by accounting for downwash in the model.

Another examples shall show the improvement of windtunnel data by estimated data from flight tests. As it is seen in figure 10a longitudinal static stability, i.e. the derivative $c_{m\alpha}$ is very well predicted by windtunnel data, extrapolation of the flight estimates, however, show a quadratic dependence on the angle of attack.

The change in rolling moment coefficient with sideslip angle, $c_{l\beta}$ (figure 10b), extracted from flight tests however, show large differences. $c_{l\beta}$ is nearly twice of that predicted by windtunnel measurements and nearly independent on landing flap position.

Another example showing th difference between windtunnel and estimated data is the effectiveness of the DLC-flaps (figure 10c). The lift variation due to flap deflection at 14 degree landing flap position is much more higher predicted by windtunnel than measured in-flight especially at large downward flap deflections.

4.2 Simulation Fidelity of Actuation Systems

As a typical example for actuation system validation the aileron actuation system of ATTAS will be used (figure 11) because it is of high order dynamics. The total system comprises the electro-hydraulic actuator connected to the control tab which drives via a mechanical spring with the aileron. Additional cables of the mechanical flight control system link left and right hand ailerons and the weel in the cockpit. The total system was modelled by an first order system with time delay and rate limitation for the actuator, all the mechanical assembly and the spring loaded tab/aileron by a second order system accounting for time delays and total air pressure. Figure 12 and 13 show that a perfect match of actuator response and high order dynamics response of the tab/aileron system at different flap/airspeed conditions could be achieved. The total aileron actuation system frequency response from flight test compared to the simulation model is shown in figure 14.

4.3 Simulation Fidelity of Sensor Systems

Important for systems simulation is that the data which are used by the flight control command and augmentation system are identical to the aircraft, as far as resolution, dynamic behaviour and time delays are concerned.

Parameter identification method can also be used to identify measurement system behaviour and measurement errors. This is done by a data compatibility check or sometimes called flight path reconstruction by using kinematic equations of aircraft motion. For example measured angle of attack must match with that reconstructed from the accelerometer and gyro measurements. From that angle of attack vane calibration could be derived. Furthermore, in-flight frequency sweep excitation are used to compare Inertial Reference System response versus rate gyro measurements showing that the IRS data have large phase delays equivalent to 40 ms which is in accordance to IRS system description (figure 15).

5. CONCLUSIONS

During the development phase the ground based simulation facility turned out as an absolute necessary tool to prove the fly-by-wire flight control concept, the functional design, data processing and software validation and qualification before first flight. The close correspondence of the ground based system simulator with the aircraft by using hardware-inthe-loop made an effective development parallel to the basic aircraft modifications possible.

Further, by checking data from ground tests in the aircraft against the simulator assist in finding discrepancies and to eliminate errors. Furthermore, the ground simulator was an big help in defining the test procedures to prove the correct functioning of the systems. These procedures are nearly identical between aircraft and the simulator.

During the operational phase of ATTAS it is usual to fly in the morning a handling qualities program by simulating specific flight control laws and in the afternoon a system for gust load alleviation or Multi DME Navigation. This flexibility of ATTAS was only possible by the intensive use of the ground based simulator where the experimenter could validate his specific experimental software and where the pilot could check the flight procedures planned for the real flight. By this different flight experiments could be prepared without burdening the aircraft. The present capability of the ground simulator ensures that software programs will operate in-flight as qualified in the ground based system.

Another advantage of using the ground based simulator is for soft- and hardware maintenance and debugging. The hardware systems of the simulator are also used as spare parts for the aircraft, so that in a failure case, equipment co..d be changed quickly.

Mandatory for that purpose is that the simulation of aircraft systems which take part in the control loops like actuators and sensors must be modelled in detail up to the data format and timing. A big breakthrough in the validation process is given by applying advanced parameter identification techniques which allow precise modelling and validation of the simulation with the required accuracy.

This technique has decisive contributed to the sucessful operation of the piloted systems simulator of the total flight test aircraft system ATTAS.

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[9] Jategaonkar, R.V.: "Determination of Aerodynamic characteristics from ATTAS Flight Data Gathering for Ground-Based Simulator. DLR-FB 91-15, May 1991.

7. FIGURES

Figure 1 ATTAS in Flight

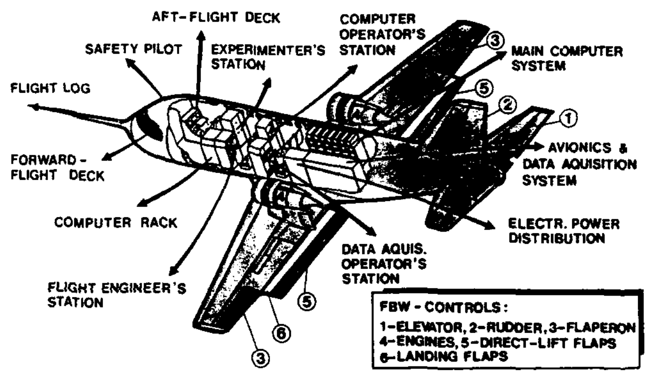

Figure 2 ATTAS Modification Overview

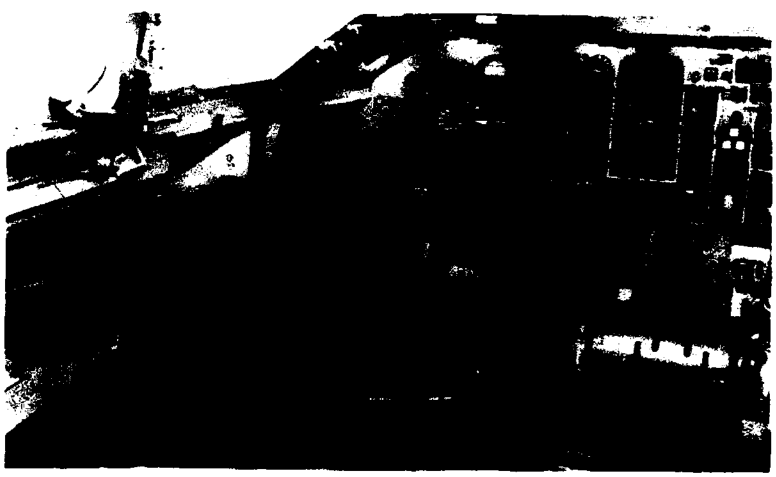

Figure 3 **Simulation Cockpit with programmable CRT's and Sidestick**

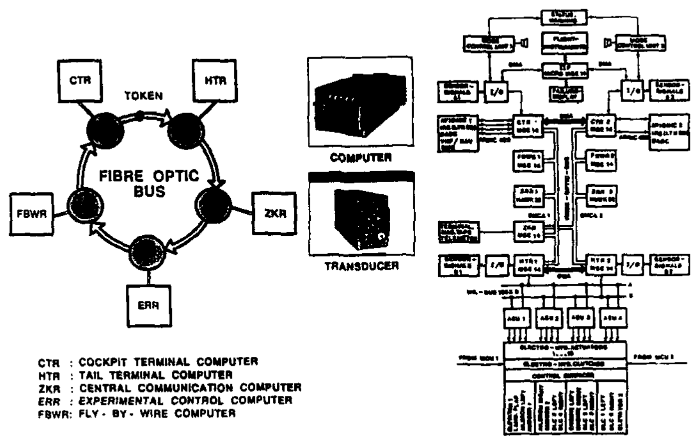

Figure 4 ATTAS Fly-by-Wire/Light Flight Control System

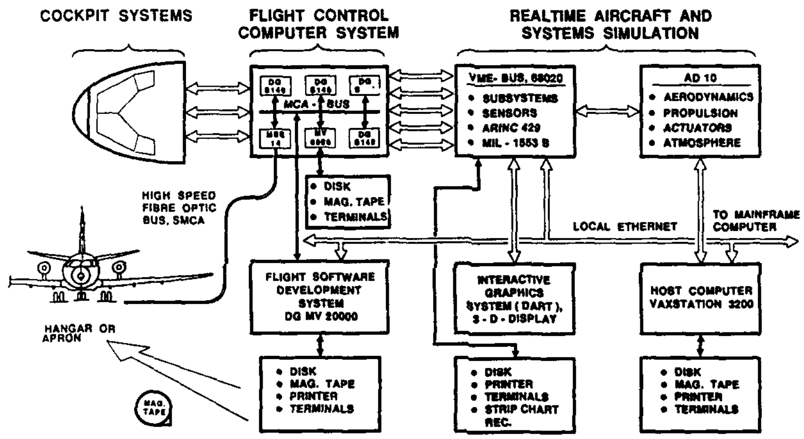

Figure 5 ATTAS piloted Systems Simulator

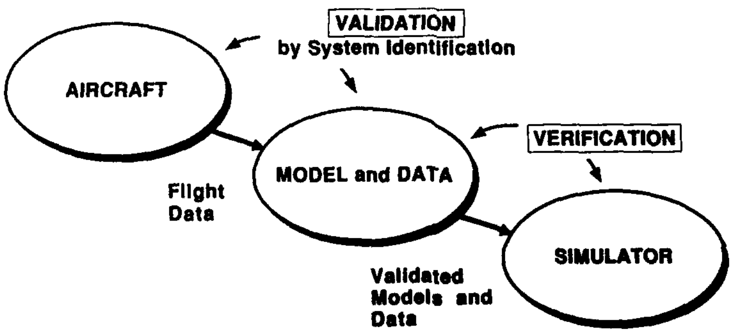

Figure 6 Simulation Validation by using System Identification

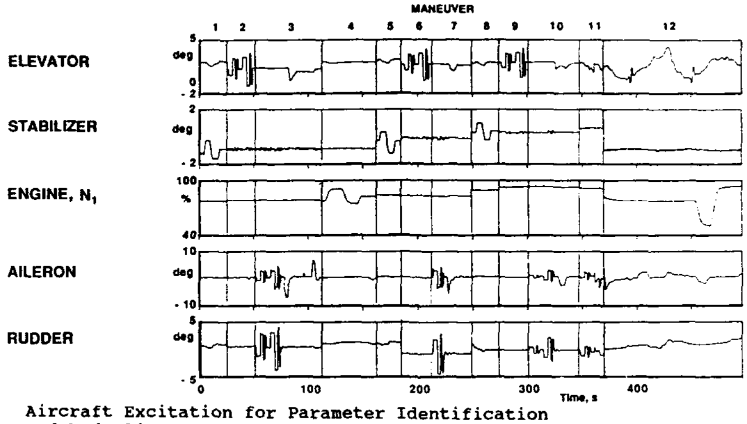

Figure 7 Aircraft Excitation for Parameter Identification and Modelling, [9]

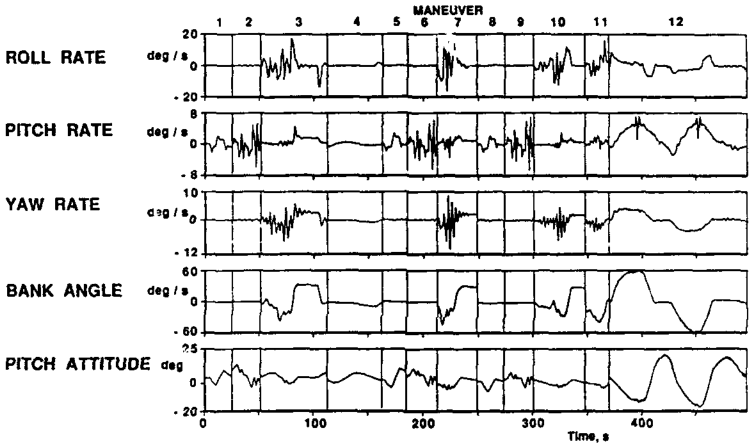

Figure 8 Flight Data/Simulation Data Comparison, [9]

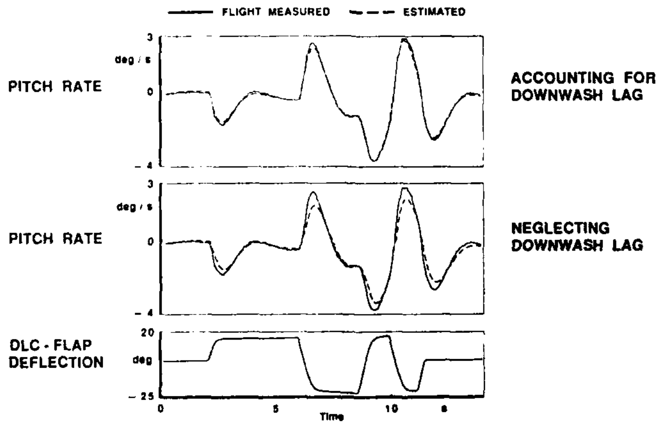

Figure 9 Downwash modelling, [9]

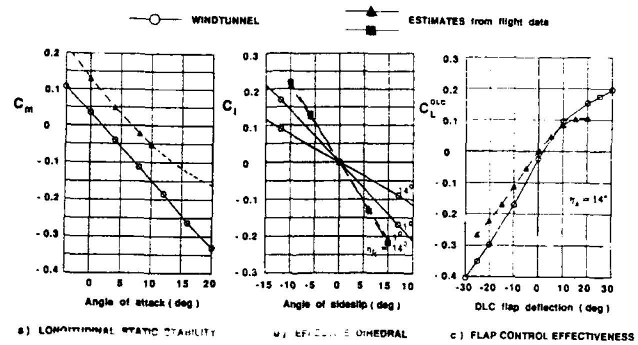

Figure 10 Windtunnel-Flight Data Comparison, [9]

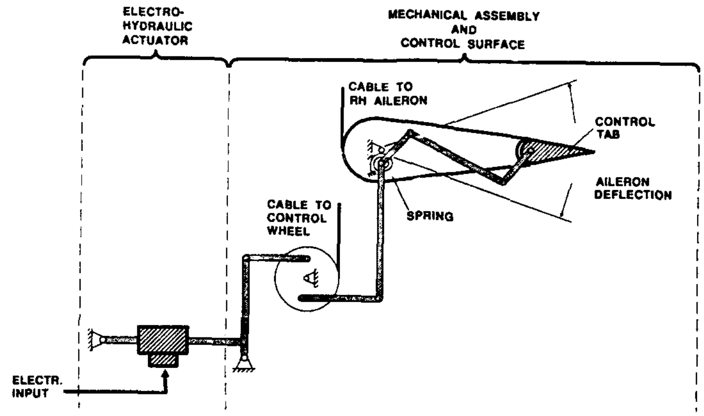

Figure 11 Aileron Actuation System of ATTAS

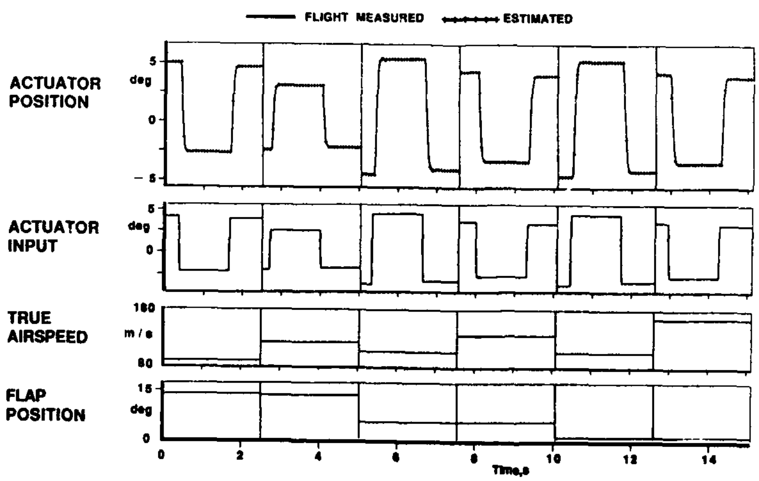

Figure 12 Aileron Actuator Simulation Fidelity

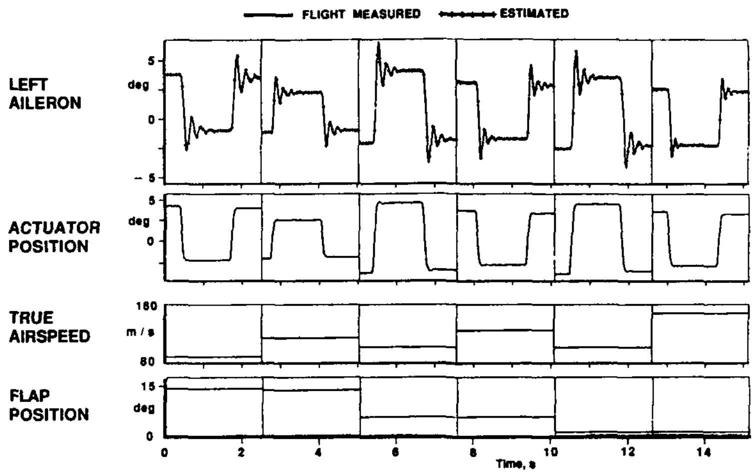

Figure 13 Control Tab/Aileron Simulation Fidelity

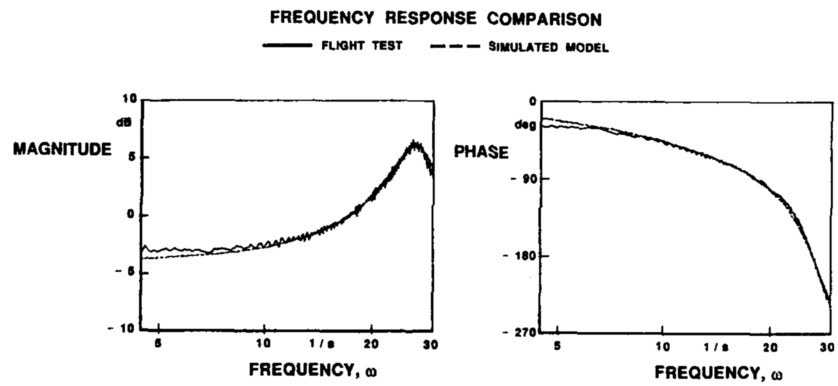

Figure 14 Total Aileron Actuation System Frequency Response

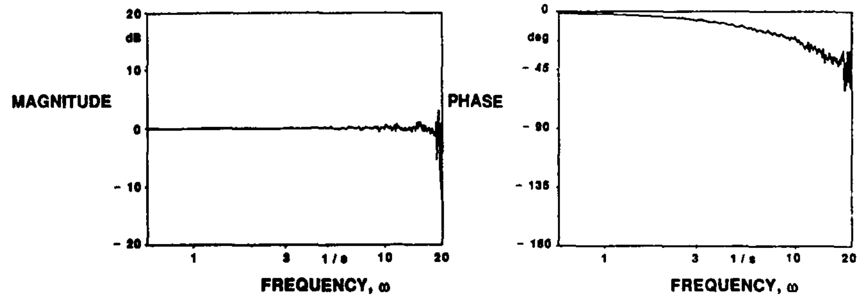

Figure 15 Inertial Reference System vs Rate Gyro Frequency Response (pitch rate)

THE USE AND EFFECTIVENESS OF PILOTED SIMULATION IN TRANSPORT AIRCRAFT RESEARCH AND DEVELOPMENT

by

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SUMMARY
Simulation requirements for military and for commercial transport aircraft are contrasted. The special problems introduced by active control are discussed with reference to earlier fighter data. Transport simulator experiments to explore these problems are described.

LIST OF SYMBOLS

FAA	Federal Aviation Administration
FQ	Flying Qualities
msec	Milliseconds
PIO	Pilot-Induced Oscillations
PR	(Cooper-Harper) Pilot Rating
TIFS	Total In-Flight Simulation
T_d	Pure Time Delay
$T_{d_{osc}}$	Time Delay to Cause a Limit Cycle Oscillation
T_e	Effective (Equivalent) Time Delay
VMS	(NASA Langley) Visual Motion Simulator
γ	Confidence Level Probability
Δ_ϕ	System Phase Lag (Loss) Angle
σ_θ	Standard Deviation of Pitch Attitude
τ_ℓ	Lag Time Constant
ω	Frequency, Radians per Second
ω_{BW}	Closed-Loop (Task) Bandwidth Frequency
$\omega_{n_{sp}}$	Undamped Natural Frequency of the Short Period Oscillation
ω_1	Lowest Structural Bending Frequency

INTRODUCTION
The flight simulator is an integral part of the commercial transport aircraft industry. It is used for configuration development, for flight crew training and certification, and in technology development and research. In the commercial aircraft world, regulations permit simulators to substitute for actual flight time in training and type-rating situations. The Federal Aviation Administration (FAA) regulates the fidelity of ground-based simulators through Advisory Circulars. Advisory Circular 120-40[1] provides criteria for evaluating and certifying airplane training simulators that generate motion and out-the-window visual scenes. There are four certification levels, A through D, representing the degrees of fidelity needed for qualifying pilots in new aircraft or in new assignments. Level D is the highest fidelity. These requirements are also used as guidelines for validating simulators that are used for aircraft certification credit in fly-by-wire transports. Advisory Circular 120-45[2] provides criteria for evaluating and certifying all other training devices. Basically, these are simulators with no motion and optional visual capability. The degrees of fidelity are defined as one through seven, seven being the highest fidelity.

In the military transport world, there are no formal requirements, even though the simulator is extensively used in developing military aircraft. However, this comparative lack of regulation is offset by a very detailed set of documented military flying qualities requirements that supplement the simulator's role.[3,4] In the current flying qualities Military Standard and Handbook,[5] there is a section on demonstrating compliance that includes suggestions and lessons learned on simulation. In any case, most manufacturers implement rather impressive high-fidelity simulators that are used in varying degrees for military aircraft cockpit development, flight control and flying qualities design, mission procedural definition, and marketing.

Recently, high-fidelity ground-based simulations have been used to design the active control systems of fighter aircraft. Unfortunately, these simulations sometimes failed to uncover certain generic problems, which led to expensive system redesign efforts and even to aircraft damage and loss. Generally, in-flight simulation did predict the problems.

Since the new generation of large transport aircraft incorporates active control technologies, we need to draw upon our fighter experience to better understand simulator fidelity and the differences between ground-based and in-flight simulation.

Phase Lag and Equivalent Delays
The two problems most commonly ecountered in the fighter experience are differences in preferred levels of command gain and of phase lag. Perhaps the most researched problem of this kind is phase lag, which can be introduced into the pilot's command path by the control system. Contributors include prefilters, structural filters, antialiasing filters, computational delays, actuation lags, etc. A number of agencies have found the lag to be significant. This is evidenced by the appearance of phase lag, in various guises, in several requirements discussed in a recent AGARD working group report.[6] The lag can be approximated with an equivalent delay defined in U.S. flying qualities documents.[4,5] The significance to the pilot of large delays is quite

dramatic, and can result in dangerous pilot-induced oscillations (PIOs) when the piloting task is demanding. In demanding tasks, the pilot must correct errors rapidly with the controls, and even relatively small delays degrade task performance. In keeping with a view of the pilot as a servo element in a closed-loop system, the terminology "high-bandwidth" has emerged for tasks that require frequent and prompt attention. In a high-bandwidth task typical of fighter operations, the sudden loss of control and PIO that can result are referred to as a flying qualities "cliff" by R. E. Smith of NASA.[6]

Application to Transports

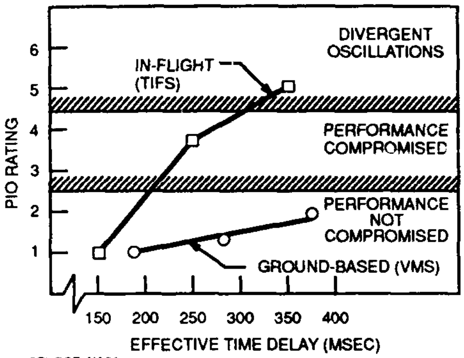
Based on these experiences in fighter design, simulation, and flight test, our first concern in active control transports is to avoid the dangerous cliffs. Unfortunately, ground-based simulators have often failed to predict cliffs due to delays in fighter flight control systems. Because the simulator is institutionalized, regulated, and inherently trusted more in the transport world than in the fighter world, it makes sense to reexamine the available data to determine how much we can trust simulation to solve the specific problem of delays for transports.

Transport aircraft, with their large size and generally undemanding (i.e., low-bandwidth) piloting tasks, might be considered relatively immune to PIOs and cliffs. Certainly much of the simulation work to date has suggested that large equivalent delays are tolerable for transport operation (Table 1).

Table 1 presents the results of both in-flight and ground-based simulation tests conducted during the 1980s to determine the effects of time delays on aircraft flying qualities. The data are taken from a number of references and apply to a variety of airplane types and piloting tasks. The only consistent trend obtained from all the tests is the fundamental and expected one that the flying qualities deteriorate as time delay increases.

The large differences between results obtained from the various transport experiments have raised questions regarding their validity. These questions encourage a natural conservatism in selecting a maximum allowable time delay for a particular design. Selecting a very low delay value may lead to higher cost in the digital flight control system design.

A valuable lesson that emerged from the fighter experience was that the effects of delays on piloting were better seen during in-flight simulation than in ground-based simulation. NASA data[11] have suggested that motion-base ground simulation does not predict the effects of delays for transports (Figure 1). Perhaps ground-based simulation does not replicate the task bandwidth very well.



SOURCE: NASA

Figure 1. Comparison of PIO Tendency Between TIFS and VMS

RECENT SIMULATIONS

Douglas Aircraft has performed several experiments on high-order augmentation effects over the past few years. For brevity, we will omit a detailed description of each experiment. Our general approach, however, was to brief the pilot on a well-defined task with equally well-defined performance measures for determining a pilot rating. We used the Cooper-Harper rating scale and employed sufficient pilots to allow meaningful statistical analysis of our results. We also gathered pilot comments. Moderate turbulence, when used, was introduced into both the visual and motion simulation, and approach and landings were performed from a flight path offset to encourage tight control of the vehicle to touchdown. The aircraft dynamics for an advanced technology transport were used for all the experiments.

We performed all the experiments described here on a motion-base simulator (Figure 2) that meets the FAA requirements for Level C certification. It has six degrees of freedom of motion and computer-generated visuals that produce realistic out-the-window twilight/night scenes. All the instruments and controls of the MD-80 aircraft are faithfully reproduced in the simulator, and its software can simulate essentially any desired aircraft dynamics.

Table 1
Transports Less Affected by Delay Than Fighters

SOURCE	MIL-F-8785C	CALSPAN SUPERSONIC CRUISE RESEARCH		CALSPAN TIFS	DOUGLAS RESEARCH		LOCKHEED RESEARCH		NASA LANGLEY	
REF NO.	4	7		8	—	—	9		10	
DATE	1980/1982	1980		1981	1986	1989	1983		1985	
TYPE OF TEST	FLIGHT			MOTION-BASE SIMULATOR						
AXIS	ALL	LONG.	LAT/DIR	ALL	LONG.	LAT	LONG.	LAT	PITCH	ROLL
FQ LEVEL	ALLOWABLE TIME DELAY AT FQ LEVEL BOUNDARY (SEC)									
1	0.10	0.12	0.17	0.20	0.44	0.33	1.10	0.40	0.5	0.3
2	0.20	0.17	0.24	0.27	0.63	0.73	1.60	0.60	1.0	0.7
3	0.25	0.21	0.28	0.43	0.76*	1.10*	2.20	0.70	1.3	0.9
CLASS	FIGHTER			TRANSPORT						

*EXTRAPOLATED

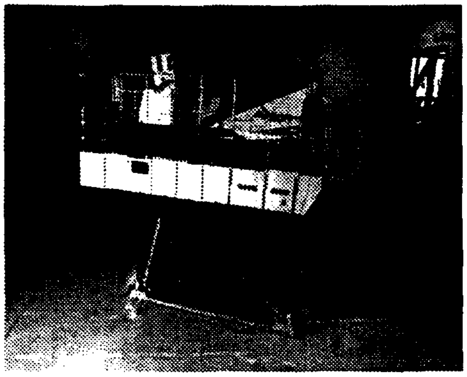


Figure 2. Motion-Base Simulator

Time Delay and Task Bandwidth

The interdependence of time delay and task bandwidth has been pointed out by Weingarten and Chalk.[8] Their hypothesized iso-opinion curves for bandwidth and time delay are reproduced in Figure 3. The curves simply relate phase loss, Δ_ϕ, to task bandwidth frequency, ω_{BW}, and effective time delay, T_e:

$$\Delta_\phi = \omega_{BW} * T_e \tag{1}$$

Each of the 10 sets of allowable time delay versus flying qualities levels from Table 1 is plotted in Figure 3 at a bandwidth where it best fits the iso-opinion curves. We extended the curves (dashed part of curves) to accommodate the very large time delays measured for the longitudinal task in Reference 9. Essentially, this procedure assigns a postulated closed-loop bandwidth to each experiment in the summary of Table 1.

Each iso-opinion curve then represents the system phase loss that the pilot tolerates for that level of flying qualities, Level 1 being 0.3 radian; Level 2 being 0.4; and Level 3 being 0.65. A time delay value from Equation (1) can be computed that would just cause a sustained oscillation in the closed-loop system. This value, $T_{d_{osc}}$, would totally absorb a 45-degree (0.785 radian) phase margin at ω_{BW}. The resulting equation and curve are also shown in Figure 3. Because $T_{d_{osc}}$ is expressed as the reciprocal of ω_{BW}, it has exactly the same form as the other curves.

Our hypothesis is that for a given level of flying qualities, the pilot will tolerate a certain amount of system phase lag. When the task bandwidth frequency is low, he can tolerate a large delay for a given level of flying qualities. When the task bandwidth is high, he can tolerate only a small delay for the same given level of flying qualities.

Using Figure 3 as a guide, we designed an experiment in which the bandwidth was a controlled variable. The pilot's task was to precisely track random flight director attitude commands with a known frequency content. The flight director displayed the error between the actual and commanded attitudes. A sample of a random pitch attitude command signal is shown in Figure 4, along with the associated power spectral density, to illustrate its frequency content (roll commands were similar). The bandwidth of the commands was varied in different runs (0.4, 0.8, 1.2 radians per second) for different levels of time delay introduced into the flight control system. Both the pitch and roll axis were

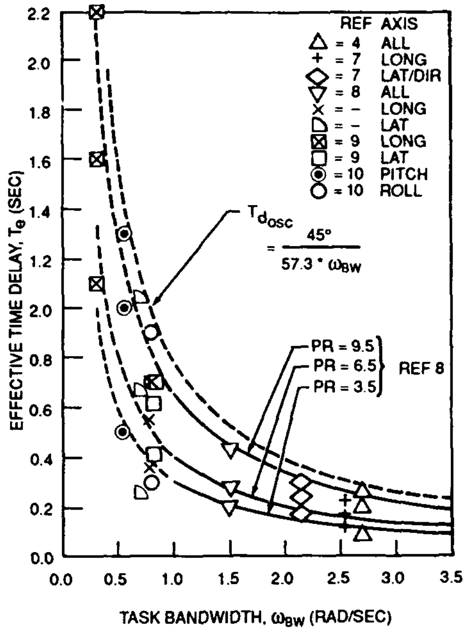


Figure 3. Delay/Bandwidth/FQ Level Relationship

tested, but not at the same time. Our experimental method was an example of a deliberately unrealistic piloting task being used to expose potential piloting problems that we knew were unlikely to emerge if we simply simulated the relatively benign piloting tasks of typical commercial operations.

Our pilot rating results appear in Table 2 and in Figure 5. Instead of plotting ω_{BW} versus T_e for isolines of constant pilot rating as in Figure 2, we plotted pilot rating against system phase loss (or lag, $\omega_{BW} \times T_e$) to see if the ratings were a function of phase lag. The results did not follow expectations in two major respects, lending some insight into flight simulation for augmented transports, especially when compared with in-flight simulator results.

First, although the 0.8 and 1.2 bandwidth data are quite close, our pilot rating data do not collapse as a function of system phase lag as hypothesized (see the upper two plots in Figure 5). For example, as phase lag increases for the 0.4 bandwidth task, the ratings change from the best obtained to the worst obtained in our experiment. Our data also do not agree with the in-flight data.

To gain some insight into these results, we plotted the pilot rating data against equivalent delay (see the lower two plots in Figure 5). Now the poor ratings for the 0.4 bandwidth cases coincide with the very large delays associated with their phase lags. For the other bandwidths, the ratings exhibit a fan shape. The fan indicates an interrelationship between ratings, delays, and task difficulty — characteristics we have seen before in fighter and other early data.[12] The form of the fan is illustrated generically in Figure 6.

Returning to Figure 5, we have overlaid on it the NASA data[11] and compared in-flight and ground-based results. Our results are consistent with the NASA ground-based data, within the very

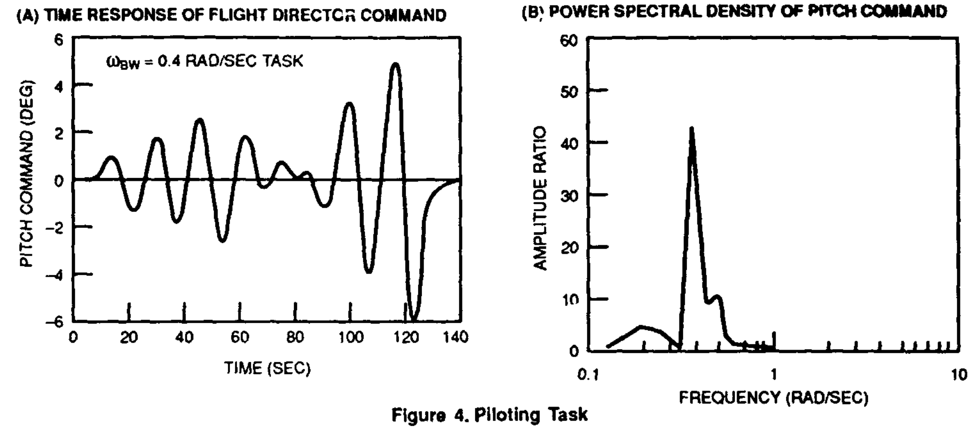


Figure 4. Piloting Task

small region studied. Our data also are not quite consistent with the in-flight data.

Second, the pilot ratings consistently improve unexpectedly (the droop in the lines to the right of the plots) when the phase lag exceeds about 45 degrees. This has not been seen in earlier data. The pilot comments suggest that the pilot was unable to perform the task at these high phase lags. He tended to "back out" of the task by lowering the bandwidth, resulting in the better ratings. And the task was confusing. Referring to Table 2, large standard deviations in the rating data at these higher bandwidths are also seen. This high phase lag rating droop is actually more a result of our simulation than a real effect. In actual flight, an increasing inability to perform the task would worsen the ratings. Backing out of the task is a luxury of ground-based simulated flight only. With this caution, we have tentatively modified the generic fan shape of Figure 6 to include the droop.

Table 2
Pilot Rating Data for Tracking Random Flight Director Signal

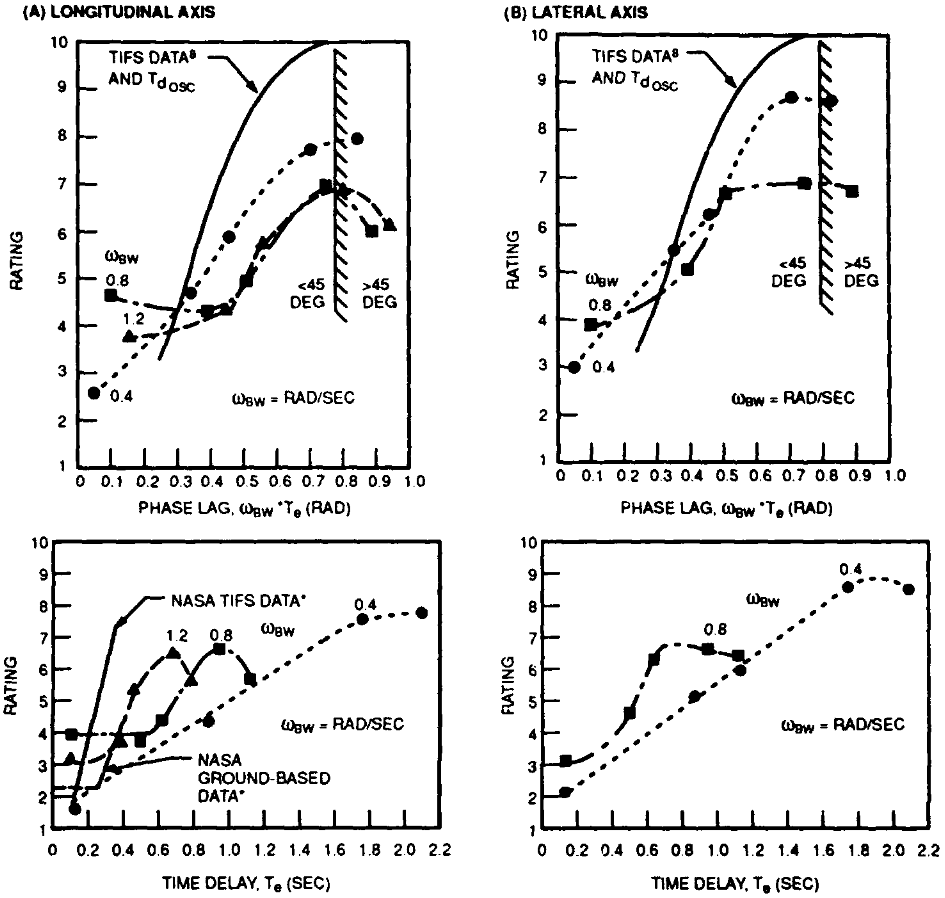
(A) LONGITUDINAL TIME DELAY VERSUS TASK BANDWIDTH

ω_{BW} (RAD/SEC)	① T_e (SEC)	$\omega_{BW} \cdot T_e$ (RAD)	MEAN PR	STANDARD DEVIATION OF PR	MIN/MAX PR FOR γ= 95% CONFIDENCE
0.4	0.125	0.050	2.6	1.1	1.9 / 3.4
0.4	0.875	0.350	4.8	1.3	3.9 / 5.6
0.4	1.125	0.450	5.9	2.4	4.3 / 7.6
0.4	1.750	0.700	7.7	2.3	6.0 / 9.3
0.4	2.088	0.835	7.9	1.7	6.7 / 9.1
0.8	0.125	0.100	4.6	1.5	3.6 / 5.7
0.8	0.500	0.400	4.3	2.1	2.8 / 3.7
0.8	0.625	0.500	4.8	1.8	3.5 / 6.0
0.8	0.938	0.750	6.9	1.9	5.6 / 8.2
0.8	1.106	0.885	5.9	2.0	4.5 / 7.4
1.2	0.125	0.150	3.8	1.4	2.9 / 4.8
1.2	0.375	0.450	4.3	1.7	3.1 / 5.4
1.2	0.458	0.550	5.8	2.3	4.2 / 7.3
1.2	0.667	0.800	6.8	2.4	5.1 / 8.4
1.2	0.779	0.935	6.0	2.1	4.6 / 7.5

(B) LATERAL TIME DELAY VERSUS TASK BANDWIDTH

ω_{BW} (RAD/SEC)	① T_e (SEC)	$\omega_{BW} \cdot T_e$ (RAD)	MEAN PR	STANDARD DEVIATION OF PR	MIN/MAX PR FOR γ= 95% CONFIDENCE
0.4	0.125	0.050	3.0	1.1	2.3 / 3.7
0.4	0.875	0.350	5.6	1.8	4.3 / 6.9
0.4	1.125	0.450	6.3	1.8	5.0 / 7.5
0.4	1.750	0.700	8.7	1.0	8.0 / 9.4
0.4	2.088	0.835	8.6	1.4	7.6 / 9.6
0.8	0.125	0.100	3.8	1.6	2.7 / 5.0
0.8	0.500	0.400	5.1	2.0	3.8 / 6.5
0.8	0.625	0.500	6.6	2.1	5.2 / 8.1
0.8	0.938	0.750	6.9	2.5	5.1 / 8.6
0.8	1.106	0.885	6.7	2.8	4.8 / 8.6

① INCLUDES 125 MSEC FOR SIMULATOR + ACTUATOR



*BANDWIDTH NOT KNOWN FOR NASA DATA

Figure 5. Mean Cooper-Harper Ratings Versus Phase Lag and Time Delay

There are some other features of our data that we cannot easily explain. For instance, the pilot ratings for the bandwidth cases of 0.8 and 1.2 were worse than we expected when the phase lag was small. We also expected that the rating for the 0.8 bandwidth would be the same or better than that for the 1.2 bandwidth. In fact, it was worse.

First-Order Lag Prefilters

First-order prefilters also produce phase lag. Figure 7 presents our motion-base simulation results for both the pitch and roll axis. We included a nominal additional delay of 125 msec to account for simulator and actuator delays. The task simulated was an approach and landing in moderate turbulence. The first-order lags degraded pilot rating up to a time constant of 0.35 second, and the ratings then stabilized. First-order lags can only introduce up to 90 degrees of phase lag, which in an equivalent system would contribute about 150 msec of equivalent time delay at most. Our result generally agrees with Table 1, i.e., transports accept more delay than fighters.

At 10 radians per second, a lag time constant of 0.35 second would introduce the same phase lag as 129 msec of equivalent time delay. Adding the nominal time delay of 125 msec, we get a total equivalent time delay of approximately 254 msec. This level of delay would be catastrophic for fighters but only Level 2 for transports. In general, it appears that prefilters in transports are not as detrimental as we once thought, but still should be used with caution.

Higher-Order Structural Dynamics

The combination of such factors as new construction materials, stretched configurations, and very-high-aspect-ratio wings can greatly increase elasticity compared with the relatively rigid construction of earlier airplanes. Because the elasticity adds higher order modes to the aircraft response, we performed a simulator study on the effects of these modes on longitudinal flying qualities. A ground-based simulator was used instead of in-flight simulation because of the possible hazards associated with our wide range of elastic dynamics.

We had postulated that the higher-order structural dynamics would become more objectionable as structural frequency decreased, and that the ratings could be correlated with the lag of the dynamics. We found that as structural frequency decreased with respect to short-period frequency, the flying

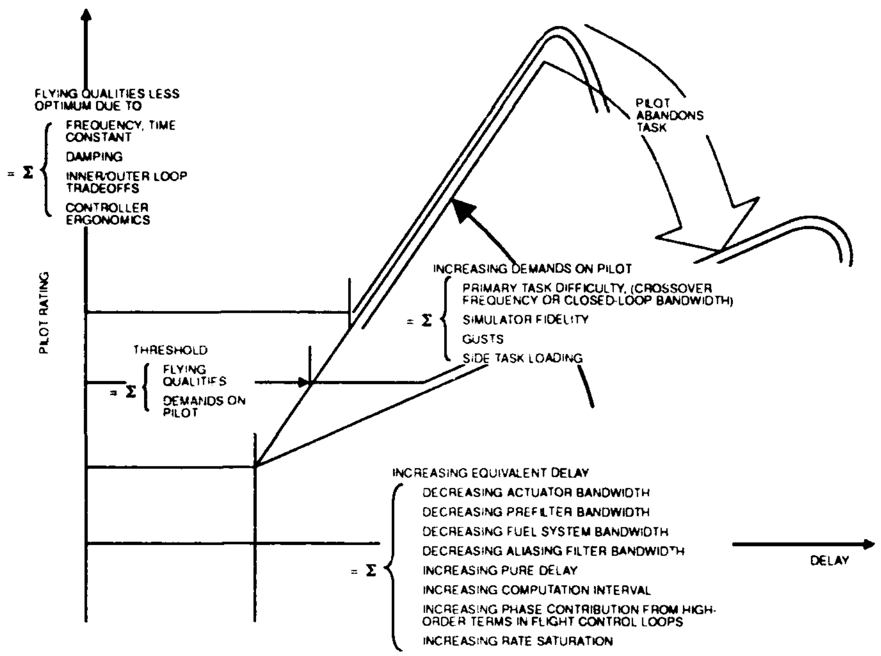


Figure 6. Generic Rating Variation With Equivalent Delay

qualities did degrade. However, the degradation was milder than we expected (see Figure 8a). Pilot acceptance of the elastic configurations was a matter of the aircraft's ride qualities rather than flying qualities. Even for the elastic configuration we considered to be the worst ($\omega_1/\omega_{n_{sp}} = 0.8$), several pilots commented that the configuration was controllable, but that the motion was confusing. Pitch tracking performance was degraded, but the pilots apparently did not notice or find it significant (see Figure 8b). The drop in the rating slope at the 1.2 ω ratio was the result of simulating only two of the five structural modes (the lowest and highest) for both the 1.2 and 0.8 ω ratio configurations. We omitted the other modes as a safety precaution because the motion at these ω ratios using all five modes was quite dramatic. The resulting motion was toned down to the extent that the pilots perceived the 2.0 and 1.2 ω ratio configurations to be similar; hence, the rating drop. This also points out that when safety is involved, even ground-based simulation has limits. From Figure 8, we proposed level boundaries for allowable aircraft structural motion in the longitudinal axes:

Level	$\omega_1/\omega_{n\,sp}$
1	7.75
2	2.50
3	0.80

As shown, the Level 3 boundary was much lower than expected. The Level 3 boundary was placed at 0.8 even though it did not

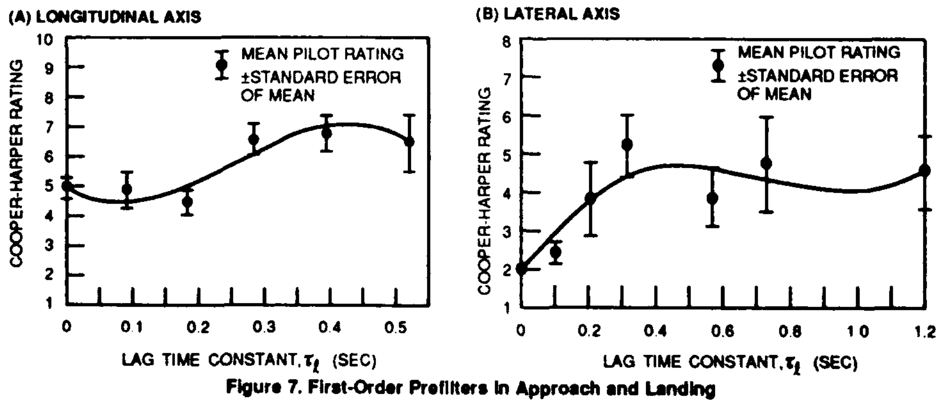


Figure 7. First-Order Prefilters In Approach and Landing

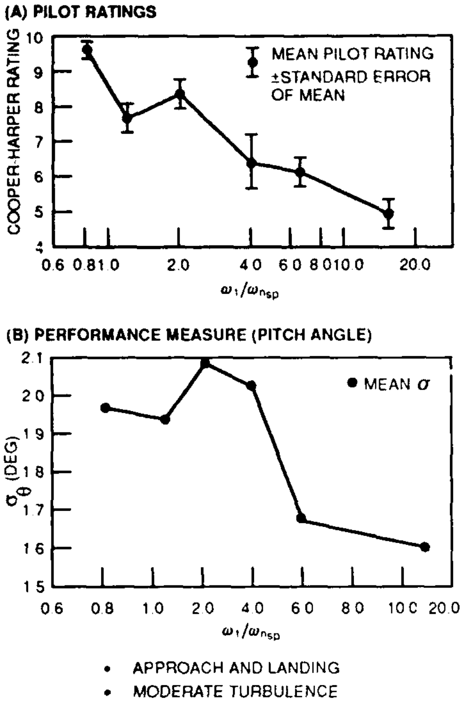


Figure 8. Ratings and Performance for Longitudinal Elastic Experiment

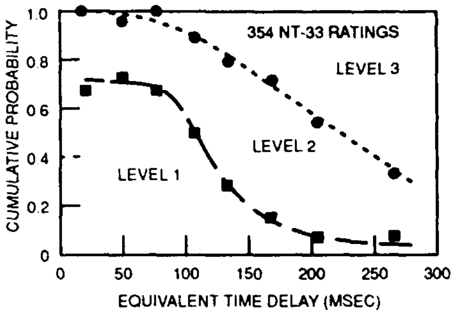


Figure 9. Probability of Worse Level Increases With Delay

quite fall on the 9.5 rating line since the pilot's comments indicated the configuration was unacceptable.

The most significant result from this structural mode experiment was that the pilots noticed the difference between the baseline rigid and elastic airplanes. They were not told which airplane was rigid and which was elastic, but all agreed the elastic airplane felt more like a real airplane. In fact, on the average, the elastic airplane was rated 1.25 points better than the rigid airplane on the Cooper-Harper scale. It seems fair to say that, when possible, implementing the structural modes of the aircraft in the simulator will help to improve its fidelity and in turn its realism, especially for flying qualities evaluations where the structural mode frequencies are low enough.

TIME DELAY VS. SAFETY OF FLIGHT

A recent study of in-flight simulation data showed that good flying qualities can translate to good flight safety. In examining large quantities of pilot rating data, we observed that time delays increase the statistical possibility of a stray loss-of-control incident. Figure 9 illustrates this by plotting cumulative probability of control loss against equivalent delay, using 354 pilot ratings from in-flight simulation experiments on fighters. This plot shows, for example, that with 100 msec of delay, about 10 percent of the configurations were in Level 3, 30 percent in Level 2, and the remaining 60 percent in Level 1. As another example, with no delay, no configurations were in Level 3. The significance of Level 3 is that loss of control becomes an issue. We have not plotted the Level 4 line denoting definite loss of control, because we had insufficient data. However, there were configurations that experienced loss of control with relatively low time delays, only 150 msec, for example.[12] Further analyses of these data are included in Reference 13.

Hoh[14] has pointed out that pilots will certify aircraft with ratings of 6. This corresponds to a time delay (for a fighter) of up to 200 msec.[4] According to the fighter data of Figure 9, the probability of a stray loss-of-control incident is quite high for that delay value. Therefore, in view of the "cliff" nature of loss of control due to delay, caution is needed in the design process when the presence of delays is suspected. In view also of the special role of simulation in transport development and training, studies to explore and improve simulator evaluation of augmented transports would seem to be urgently needed.

CONCLUSIONS

The ground-based simulator is a valuable research and development tool for exploring active control characteristics of the new generation of transports. The value is evidenced by our recent simulations, which demonstrate rational trends of pilot opinion with variations in delays, lags, and other high-order dynamics. However, more accurate calibration of the ground-based equipment against in-flight results is needed. We need to redefine ground-based fidelity, especially for these high-order effects.

Future ground-based simulators will benefit from advances in display and motion quality, and from improved computer speed and capacity. Equally important, though, is the need to improve piloting tasks and experimental protocols, even if that involves tasks that appear unrepresentative of general operational use. We need to synthesize in our simulation laboratories the ingredient to make our ground-based results match the in-flight data.

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AN EVALUATION OF IFR APPROACH TECHNIQUES: GENERIC HELICOPTER SIMULATION COMPARED WITH ACTUAL FLIGHT

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SUMMARY

Although flight simulators are now extensively employed in aerospace research and development programs, it is still necessary from time to time to verify the findings achieved during simulator tests against actual flight tests. This paper describes such a comparison process using a generic helicopter simulator and flight tests carried out in the National Aeronautical Establishment's Bell 205 research helicopter. The project was designed to establish some initial application boundaries for the newly commissioned helicopter simulator. Hence the validation process took place in reverse order, with the helicopter simulator runs performed after the flight tests.

The simulator was based on the ARMCOP software package and employed parameters for a Bell 205. The flying task involved pilot ratings of flight control modes and flight directors to be used in decelerating IFR approaches. The simulator was modified to match the flight test hardware and software. Six evaluation pilots flew four helicopter configurations selected for evaluation. In addition several simulator configurations were employed in order to assess their impact on the validation process. These configurations were:

(1) motion on and off,
(2) forward display on and off.

It was found that the simulator configuration had no significant impact on the experimental results for the present tasks. In general there was good agreement between the simulator findings and the flight test results. The exception was for a flight control mode that could not be simulated precisely with the present hardware. For this case the simulator was judged to be easier to fly than the actual aircraft.

1. INTRODUCTION

The Flight Research Simulator at the University of Toronto Institute for Aerospace Studies has been recently upgraded to include a generic helicopter capability. In order to enable us to cooperate closely with the Flight Research Laboratory of the National Aeronautical Establishment (NAE) (now the Institute for Aerospace Research) the first helicopter to be simulated was the NAE Bell 205. Upon completion of the facility development a process of validation was carried out. This took place in two parts. The first was the validation of the Bell 205 simulation itself. The second was the beginning of an assessment program to determine the kind of research that could be carried out successfully on the simulator.

In the past, validation efforts involving helicopter simulators have demonstrated that achieving a good match between the simulator and the actual flight vehicle is no easy matter. In Reference 1 the simulation of an Agusta A109 is described (employing the same ARMCOP flight equations package as the present project). This was a fixed-base simulation employing 4 windows of external display on the Ames Vertical Motion Simulator (VMS). It was found that the simulator exhibited low-speed dynamic response which was considerably less stable than the real helicopter. It was felt that the lack of motion and fine visual cues increased the difficulty of simulator tasks for the pilot. It was reported in Reference 2 that a Black Hawk helicopter simulation on the VMS (employing 4 windows of external display and motion) appeared to the test pilots to be less well damped than the actual helicopter in all axes. Cooper-Harper ratings assigned to the simulator tended to be 1-1/2 to 2 points higher than for the actual helicopter. It was felt that certain key cues required to accomplish low speed and hover tasks were not present.

In Reference 3 a study is reported involving the VMS in a simulation of the Harrier aircraft performing a hovering task out of ground-effect. The use of special visual targets designed to provide precise positional information in both the real flight and in the simulator resulted in good agreement between actual flight and simulated flight. The authors concluded that inadequate correspondence between

the simulator visual scene and the real world was largely responsible for previous inabilities to satisfactorily validate simulations of hovering aircraft.

Reference 4 reports on the evaluation and upgrading of a real-time simulation model of the UH-60A Black Hawk helicopter employing Sikorsky's Gen Hel program. They found that based on a mix of piloted and unmanned simulations, they were able to achieve good agreement with flight test data and other off-line computer simulations of the helicopter. A blade-element rotor aerodynamics model was used and the simulation required a 50 Hz iteration rate.

2. SIMULATOR HARDWARE

The UTIAS Flight Research Simulator incorporates a cab mounted on a 6 degrees-of-freedom CAE Series 300 motion-base (Reference 5) (see Figure 1). Two cockpits are included inside the cab; a jet transport in the front and a generic helicopter facing rearward. The helicopter workstation is shown in Figure 2. The simulation is run with a 33 Hz iteration rate.

The seat and pilot controls are from a Bell 205. The controls were counterbalanced to represent the NAE Bell 205 with its control loading system deactivated. In order to provide the flexibility desired in a research simulator it was decided to employ an electronic flight instrument system (EFIS) run on a Silicon Graphics IRIS 3130 workstation. The cockpit display was the workstation's 19 inch (48 cm) colour monitor running in the 60 Hz noninterlaced mode and updated at 30 Hz. A touchscreen mounted on the face of the monitor was used for pilot inputs.

The forward visual scene was generated by a second IRIS 3130 workstation. The full colour display was presented with a resolution of 768 horizontal lines with 1024 pixels per line. It was run in the 33 Hz interlaced mode and was updated at 33 Hz. The monitor was viewed through an infinity optics unit situated above the EFIS producing a virtual image of the monitor screen at optical infinity. The display field-of-view was 29° vertical by 40° horizontal.

The digital sound system was based on recordings made in the NAE Bell 205 cockpit.

3. FLIGHT EQUATIONS

The simulation routine for solving the flight equations was ARMCOP, developed by NASA and the U.S. Army Aviation Systems Command. ARMCOP is a nonlinear, total force and moment model. It has 10 degrees-of-freedom: 6 rigid-body, 3 rotor flapping, and rotor rotation. For helicopters with non-teetering rotors, the 3 rotor flapping degrees-of-freedom are the longitudinal and lateral tilts of the rotor plane as well as the coning angle. For teetering rotor systems such as the Bell 205, the coning angle is preset and remains constant. In this case we are left with a total of 9 degrees-of-freedom.

4. MOTION SYSTEM SOFTWARE

The simulation employed an adaptive washout algorithm described in References 5 and 6. The algorithm's parameters were selected by carrying out evaluation flights employing a test pilot familiar with the NAE Bell 205. The details of this process are described in Reference 5.

In addition to motion cues related to rigid body motions of the simulator, a rotor buffet cue was also generated. This had a frequency equal to twice the rotor rotational frequency and produced a sinusoidal heave acceleration with an amplitude dependent upon flight conditions.

5. SIMULATOR TIMING

In order to reduce the time delays associated with the use of digital computers in the simulator, care was taken in structuring both the hardware and the software.

To synchronize the forward visual display with the solution updates of the flight equations on the PE 3250, the buffer swap signal from its IRIS 3130 workstation (indicating the start of a new display scene) is used as the system clock. It is sent to the PE 3250 and initiates the sampling of the pilot's controls and the next solution cycle. This clock runs at 33 Hz in the present simulation. In estimating the visual display time delay from pilot control input to scene display on the monitor, a number of items must be considered:

(1) the sampling of the pilot's controls at 33 Hz by the analog-to-digital converter can be represented by a 15 ms time delay,

(2) the processing of the flight equations by the PE 3250 and the scene calculations and graphics processing by the IRIS workstation adds 60 ms to the time delay,

(3) the time taken to display the scene on the colour monitor can be considered to add 15 ms to the overall time delay,

(4) the predictor form of the numerical integration employed in solving the flight equations on the PE 3250 reduces the time delay by 60 ms,

(5) the use of visual display time delay compensation (see Reference 7) on the angular degrees-of-freedom reduces their time delay by a further 30 ms.

Overall, the time delay in the visual display of translational position is 30 ms while there is no time delay on the display of angular attitude.

The instrument display is running at 30 Hz and is not synchronized to the PE 3250 processing cycle. For this reason the time delay for the instruments is not constant. The display of attitude, heading and position have time delays ranging from 15 to 45 ms while those for rate displays range from 45 to 75 ms.

The motion system is more complex than the visual system because the motion drive software contains high-pass and low-pass filters that influence its response. The motion hardware also has a dynamic effect. Measurements performed on the UTIAS Flight Research Simulator indicate that the transport time delay component of these dynamic effects is typically 50 ms for the angular degrees-of-freedom and 37 ms for the translational degrees-of-freedom.

6. VALIDATION OF THE BASIC BELL 205

As reported in References 5 and 8 the basic Bell 205 was validated using 3 different methods: (i) by comparisons with actual NAE Bell 205 flight test data; (ii) by comparisons of stability derivatives with those determined from the NAE flight test data; and (iii) by piloted simulator flights. As a result of these tests several alterations and

additions were made to the ARMCOP software.

(1) In its original form ARMCOP solved the rotor equations in a wind axis system. This caused difficulties near hover where the direction of the wind relative to the helicopter body axis frame could change rapidly. This problem was overcome by altering the computer code to solve the rotor equations in the helicopter body axis system.

(2) The landing gear model in ARMCOP was modified to represent the skids of the Bell 205. This was carried out in order to allow the simulator to be set down following hover and was only an approximation to the real helicopter skids. If the simulator is ever used to study landing operations in detail then a more complex model will be required.

(3) One important dynamic aspect of the Bell 205 not included in ARMCOP is the stabilizing bar. This is a simple two-axis stability augmentor. This was simulated by feeding back helicopter pitch and roll rates to the swashplate angles after passing them through first order low-pass filters.

(4) Several problems were found relating to the power train. In particular RPM fluctuations were excessive in some maneuvers. Changes to the model to correct this involved the inclusion of a fuel flow controller model and a feedforward from the collective control to the fuel scheduler. In addition, parameter values were adjusted to more closely match the response to the NAE Bell 205 helicopter.

(5) The tail rotor on the NAE Bell 205 has been modified by employing a larger one from a Bell 412. This has been accounted for in the ARMCOP simulation by increasing the solidity ratio of the tail rotor.

(6) Changes were made to the ARMCOP program and parameter values to solve pitch trim attitude problems and insufficient damping in pitch. (Similar problems were reported in Reference 1.) A sideslip problem was fixed by replacing an incorrect fuselage sideforce parameter.

Once all of the above changes had been implemented the test pilot judged the simulator to be a good representation of the NAE Bell 205 for modest maneuvering not involving nap-of-the-earth flight and hovering tasks. These restrictions were felt to be due to the limited visual field-of-view and limitations of the ARMCOP flight model.

7. VALIDATION OF A SIMULATOR APPLICATION

Based on the findings of other research groups and the opinion of our test pilot it would appear that our generic helicopter simulator is not currently suited to low-level flight and hover-tasks. Thus the task selected for the initial simulator application was a decelerating IFR approach to landing. The baseline task was flown on instruments from an initial altitude of 500 ft. (152 m) above ground level (AGL) through a simulated overcast extending upward from 50 ft. (15 m) AGL. Thus the visual display only became available to the pilot for a short period at the end of the landing approach and was not critical to the primary flying task.

The original study into decelerating IFR approaches was performed by the NAE (Reference 9) using their Bell 205. Their data from actual flight tests served as the reference against which the helicopter simulator results were compared. The plan was to duplicate the actual flight trials in the simulator and to judge the validity of the simulator application by comparing the two sets of experimental results.

In order to carry out the original experiment, the NAE augmented the longitudinal and lateral stability of their Bell 205 to represent a modern IFR helicopter. Two flight control modes and a three-cue flight director were developed as pilot aids and employed in the study. The same additions were made to the present helicopter simulator as described below.

7.1 Yaw Axis Control Modes

Two flight control modes were implemented. Both were designed to allow the pilot to fly landing approaches with their feet on the floor (i.e., no pedal inputs required). The details of the control laws are contained in References 5 and 9.

The *turn coordination mode* was designed to maintain sideslip at an acceptably small value during maneuvering while on the landing approach. The *heading hold mode* was designed to maintain a reference heading to within 5 degrees irrespective of the lateral cyclic input.

7.2 Flight Director

A three-axis flight director is used to command pilot inputs on the longitudinal cyclic, the lateral cyclic and the collective controls. Ground speed error is used to command pitch attitude, height error is used to command collective input, and lateral position error is used to command bank attitude. The control laws for the display symbols are described in Reference 9.

Pitch Flight Director

The velocity command is the ground speed profile (V_{GC}) of Figure 3. This represents a decelerating landing approach starting from 60 kts. (31 m/s). Measured Bode plots of the transfer function relating longitudinal cyclic input to symbol displacement indicate that this director behaves like a simple integration of the longitudinal cyclic (k/s) over the entire frequency range of pilot control. The pitch limiter in the forward path, set at ±10 degrees around the trim pitch angle of approximately 5 degrees, provides a necessary angular limit to speed corrections when errors become large. Overall scaling of the director was 0.43 inches (1.1 cm) of symbol movement per 10 kts. (5 m/s) of steady state error.

Roll Flight Director

Like the pitch flight director, the roll flight director behaves like a simple integration between lateral cyclic input and symbol displacement. The lateral command is the localizer location and lateral error represents lateral deviations from the localizer. Roll angle scaling was set at approximately

1/2 degree per ft. (1.64 degrees per m) of steady state localizer error. Overall flight director scaling was 0.30 ins. (0.76 cm) of symbol movement per 100 ft. (30.5 m) of steady state localizer error.

Collective Flight Director
The height command is based on a 6° glide slope. The Bode plots of the transfer function from collective input to symbol displacement demonstrate a constant amplitude ratio over the normal frequency range of pilot control, consistent with the collective position director concept. Overall scaling of the director was approximately 0.25 ins. (0.64 cm) symbol deflection per 25 ft. (7.6 m). of steady state glide slope error.

7.3 Flight Director Display

The flight director display symbol (#29) is depicted in Figure 4 along with the complete EFIS. The longitudinal and lateral cyclic commands are represented by the displacement of the flight director circle away from the centre of the display. One should fly towards the circle to reduce tracking errors to zero. For example, if the circle is above and to the left of the centre of the display the proper response is to bank to the left and pull up (i.e., left lateral cyclic and aft longitudinal cyclic stick inputs). The stick symbol extending up from the top of the circle (or down from the bottom of the circle) represents the collective command. If the stick is up then reduce (push down on) the collective. The error has been reduced to zero when the stick has shrunk to the edge of the circle symbol.

7.4 Experimental Plan

The purpose of the test program was to compare the performance and handling qualities ratings achieved during an actual flight test program with those produced using the helicopter flight simulator.

IFR Landing Approach Task
The flight evaluations carried out by the NAE and reported in Reference 9 involved capturing and following a 6° linear glide slope while simultaneously decelerating according to the ground speed profile shown in Figure 3. An audio alerting signal was included to warn the pilot when he has entered the region where the deceleration profile exists.

Two primary types of landing approach techniques were evaluated; the crab technique and the sideslip technique. These techniques are applied in the presence of a crosswind in order to maintain the helicopter on the localizer during the landing approach. In the crab technique the helicopter is flown with zero bank angle and sufficient heading angle (away from the runway heading) to maintain its ground track along the localizer in the presence of the crosswind. In the sideslip technique the helicopter heading is maintained equal to the runway heading. A forward slip is used (with the helicopter banked towards the oncoming crosswind) to generate sufficient airspeed at right angles to the localizer to cancel the effect of the crosswind, thus maintaining the ground track along the localizer. A third technique termed the blending technique was also evaluated in which the landing approach was begun using the crab technique and then changed to the sideslip technique near the end of the maneuver when the ground speed dropped below 40 kts. (21 m/s). At the point of transition the heading hold autopilot captures the current helicopter heading and in general this will not be the runway heading. Thus the final portion of the approach is flown with a combined crab and sideslip. This should prevent excessive values of heading offset and bank angle as the ground speed drops off towards zero.

In these trials the following combinations of approach technique and yaw axis control mode were always employed:

(1) (crab technique) + (turn coordination mode),
(2) (sideslip technique) + (heading hold mode).

Simulator Flight Test Procedures
The starting location of the helicopter is 500 ft. (152 m) AGL, on the localizer, heading along the runway centreline and 6,800 ft. (2,073 m) back from the runway threshold. The helicopter is trimmed for level flight at 60 kts. (30.9 m/s) indicated airspeed. The pilot is informed by the experimenter concerning the current test parameters and the controls are sampled by the simulator program to establish their trimmed positions. At this time the visual display is turned on. When the pilot indicates that he is ready the flight begins in the trimmed state. After 5 seconds the wind fades in linearly over the next 6 seconds (a 15 kt. (7.7 m/s) constant crosswind either 45° from the left or the right; see Figure 3). During this portion of the flight the task is to maintain level flight along the localizer and to establish a ground speed of 60 kts. (30.9 m/s). The cyclic commands from the flight director are used to assist in this task. The pilot continues towards the runway at 500 ft. (152 m) AGL until he captures the glide slope from below at a distance of 4,760 ft. (1,451 m) from the runway threshold. He then continues down the glide slope at a ground speed of 60 kts. (30.9 m/s) until he reaches the start of the deceleration curve at 3,550 ft. (1,082 m) from the threshold. At this point an audio warning is heard and the decelerating portion of the approach begins. If the flight is being conducted through cloud, the helicopter will break out of the cloud upon descending through 50 ft. (15 m) AGL and visual contact with the airport will be made. At a height of 40 ft. (12 m) AGL (or if the ground speed drops below 25 kts. (12.9 m/s)) the run is terminated.

Simulator Independent Variables
Because one purpose of this study was to investigate the influence of flight simulation on helicopter/pilot performance, several simulator configurations were employed. These were:

	Condition	Symbol
(1)	Motion system on	M
(2)	Motion system off	N
(3)	VFR visibility (clear)	V
(4)	IFR visibility (zero)	I

Experimental Sequence
In order to keep the size of the experiment within reasonable bounds it was necessary to restrict the combinations of factors employed. The following 4 flight director/control mode configurations were selected:

C1 — (crab technique) + (turn coordination mode) + (3 cue flight director)

C2 — (sideslip technique) + (heading hold mode) + (3 cue flight director)
C3 — (blending technique) + (blending mode) + (3 cue flight director)
C4 — (crab technique) + (turn coordination mode) + (raw display)

In the above, *raw display* refers to a case in which the 3 cue flight director is turned off. The pilot then uses the localizer and glide slope bugs and the commanded ground speed bug (see symbols #27, #28 and #39 in Figure 4).

The visual display options were VFR (clear) (see Figure 5) and IFR (zero visibility) with a greyed-out visual display.

The matrix of the 14 test cases selected is given in Table 1.

It was decided that each pilot subject would perform 4 replicates of each of the cases listed in Table 1. The order of presentation of the cases was randomized but the 4 replicates were carried out one after the other with a minimum of delay between runs. This was done in order to help the pilot to produce a good handling qualities rating for each case.

Each block of 4 replicates took approximately 12 minutes to run including the time consumed in providing pilot ratings. The production runs for each pilot were run in 4 one-hour blocks. Only 2 one-hour blocks (with a half-hour break between them) were performed on any one day.

7.5 Subjects

Six male subjects took part in the experiment. Two (S1 and S2) were test pilots, three (S3, S4 and S5) were civilian helicopter pilots and one (S6) was a project engineer. Their flight experience is detailed in Table 2.

7.6 Experimental Measures

Six objective measures and three pilot evaluations were employed.

The objective measures were based on glide slope and localizer error measured in feet and ground speed error measured in knots. The objective measures were obtained after each run. The first three objective measures were the standard deviations of these variables computed from the time the helicopter passed the nominal glide slope capture point (4,760 ft. (1,451 m) from the end of the runway) until the end of the run when it descended through 40 ft. (12 m) AGL (or the ground speed dropped below 25 kts. (12.9 m/s)). The final three objective measures were the values of glide slope, localizer and ground speed error at the end of the run.

The pilot evaluations were those employed in Reference 9: Cooper-Harper handling qualities ratings (see Figure 6), a modified Cooper-Harper scale for workload rating (see Figure 7), and a certification related assessment (see Figure 8). Pilot evaluations were obtained after each block of four identical runs.

The pilots were asked to refer to Figures 6 to 8 (provided in the simulator) while making their decisions, and to follow the prescribed decision-making process before giving each response.

Adequate performance (as required in the Cooper-Harper scale) was taken to be ±25 ft. (7.6 m) of localizer error, ±25 ft. (7.6 m) of glide slope error and -1 to +5 kts. (-0.5 to +2.6 m/s) of ground speed error.
(Note that the flight control system is such that perfect tracking of the flight director results in a ground speed at the end of an approach that is 2 kts. (1 m/s) above the nominal profile.)

The localizer error bug (symbol #27 in Figure 4) was scaled at 3 degrees per division when the aircraft was outside a 1900 ft. (579 m) radius from the threshold, and became 100 ft. (30.5 m) of lateral displacement per division when inside this radius. (This radius corresponds to the distance where a 100 ft. (30.5 m) lateral offset subtends a 3 degree localizer error.)

The glide slope error bug (symbol #28 in Figure 4 was scaled at 1.5 degrees per division outside a 1900 ft. (579 m) radius from the threshold, becoming 50 ft. (15 m) of vertical displacement per division inside this range.

7.7 Training

The pilots were trained by having them fly the experimental cases listed in Table 1. Training included the giving of pilot ratings according to the experimental plan. A pilot was considered to be trained when

(1) he felt trained, and
(2) the experimenter felt he was trained, and
(3) he consistently achieved localizer and glide slope errors of less than ±25 ft. (7.6 m) and ground speed errors in the range -1 to +5 kts. (-0.5 to +2.6 m/s) at the end of the approach when using the flight director.

8. RESULTS AND DISCUSSION

8.1 Objective Measures

Sample traces of glide slope error (high-positive) and localizer error (right-positive) along the 6° landing approach path for the present experiment (C3, blending technique, I/M) are given in Figures 9 and 11. One sample trace for each of the 6 pilots is included. Figures 10 and 12 show data from Reference 9 for the same case. From Figures 9 and 10 it can be seen that glide slope tracking in the simulator was similar to that in flight with perhaps better average performance. From Figures 11 and 12 it would appear that similar localizer tracking performance was achieved in both cases.

The detailed data on the objective measures and the results of several analyses of variance (ANOVA) performed on these data are presented in Reference 5. Of interest in the present paper is the influence of the simulator configuration on the task performance. (Since no performance data were presented for the flight tests in Reference 9 it was not possible to make any quantitative comparisons between simulator and actual flight using the objective measures.)

Individual ANOVA tests were performed on the 6 objective measures using the mode configurations (C1, C2, C4) as one factor and the simulator configurations (I/M, I/N, V/M, V/N) as a second factor. Only two of the 6 objective measures

(standard deviation of localizer error and final glide slope error) indicated that the simulator configuration was a significant factor at the 1% level. This lack of a consistent indication was interpreted to mean that the simulator configuration was not critical in the present study. Figures 13 and 14 show typical performance results for the range of simulator configurations.

8.2 Pilot Evaluations

The pilot evaluations (see Figures 6 to 8) produce results in the form of a single number for each application. There is some uncertainty about the validity of performing statistical operations on these numbers (such as averaging, ANOVA, etc.). For this reason all of the raw data are presented in this paper and no ANOVA has been carried out on them. The handling qualities ratings are presented in Figure 15. The workload ratings are presented in Figure 16. The IFR certification assessments are presented in Figure 17.

Consider the handling qualities results of Figure 15. Three horizontal lines have been drawn across these figures. They represent the mean and extreme values reported in Reference 9 based on 5 evaluation pilots. The first thing to note is the reasonable agreement between the present experiment and Reference 9 in the cases of flight director/control modes C1 and C4. Overall, the simulator ratings are about one point lower (better) than those achieved in flight. There could be many reasons for this but it is suspected that two factors dominate:

(1) In flight, uncontrolled atmospheric effects due to turbulence and wind shear would tend to degrade handling qualities ratings and increase workload.

(2) In flight, the signals used to generate the flight director display were obtained from physical sensors having the usual imperfections while the simulator employed clean and exact signals. This would tend to make the simulator easier to fly.

In the case of C2 and C3 it appears that the current tests produced significantly better (lower) handling qualities ratings. Since both these configurations employ the heading hold mode it is suspected that the present heading hold implementation is easier to fly than the one that the NAE employed during their flight tests.

Of the 6 subjects employed in the present study only S1 and S2 were experienced in giving handling qualities ratings. However, from the data of Figure 15 it appears that the ratings provided by the other 4 subjects were only slightly more variable.

There is no clear trend in the handling qualities ratings as the simulator conditions are changed. This is consistent with the performance results reported above.

The workload ratings of Figure 16 follow the same trends noted above for the handling qualities ratings.

The raw IFR certification assessment data of Figure 17 indicate that the non-IFR rated pilots from time to time had difficulty in providing consistent ratings. Figure 18 superimposes the present results on a figure from Reference 9 giving the percentage of pilot ratings in each of 3 categories. The following transformation between rating and certification level was used:

Rating	Certification Level
1	1-pilot certifiable
2,3	2-pilot certifiable
4	uncertifiable

It can be seen that for the case presented (I/M matches most closely the flight trials) that for flight director/control modes C1 and C4 there is perfect agreement between the present experiment and Reference 9. C2 and C3, as expected, produced widely different results with the present simulation indicating single pilot certifiability. This is a direct result of the corresponding handling qualities and workload levels and follows from the properties of the simulated heading hold mode.

9. CONCLUSIONS

(1) The validation process carried out on the basic Bell 205 helicopter simulator confirmed the findings of previous investigators: missing cues in the CGI (computer generated imagery) visual display system limit the range of flying tasks that can be flown; the ARMCOP routine tends to produce a simulated helicopter with less dynamic stability than the actual helicopter. For the present generic helicopter simulator these and related effects preclude its application in tasks involving aggressive maneuvering, nap of the earth flight and hovering. However, the simulator was judged to be a good representation of the NAE Bell 205 for all other flying tasks investigated.

(2) The validation of a flight simulator against flight test data is necessary but not sufficient to ensure adequate fidelity from the pilot's point of view. A final tuning process with the pilot in the loop is also required.

(3) The instrument landing approach task appears to be insensitive to the simulator configuration (motion on/off, visual display on/off).

(4) The heading hold mode employed in the NAE flight tests could not be accurately simulated based on available information. The heading hold mode developed and flown in the present simulator study was easier to fly than the actual flight test article.

(5) Except for tasks employing the heading hold mode, the current Bell 205 simulator reproduced the IFR landing approach flight test findings of Reference 9 with reasonable accuracy. The results included handling qualities ratings, workload ratings and IFR certification assessments.

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Table 1. Test Cases

Case	Configuration	Motion	Visuals
C1, I/N	C1	Off	IFR
C1, I/M	C1	On	IFR
C1, V/N	C1	Off	VFR
C1, V/M	C1	On	VFR
C2, I/N	C2	Off	IFR
C2, I/M	C2	On	IFR
C2, V/N	C2	Off	VFR
C2, V/M	C2	On	VFR
C3, I/N	C3	Off	IFR
C3, I/M	C3	On	IFR
C4, I/N	C4	Off	IFR
C4, I/M	C4	On	IFR
C4, V/N	C4	Off	VFR
C4, V/M	C4	On	VFR

Table 2. Pilot Experience

	Fixed Wing			Helicopter			
Pilot No.	Aircraft Hours	Simulator Hours	IFR Rating	Aircraft Hours (Total)	Simulator Hours	Bell 205 Hours	IFR Rating
1	6,500	300	Yes	1,500	75	1,000	Yes
2	8,200	250	Yes	1,500	60	1,000	Yes
3	500	20	No	550	0	0	No
4	200	10	No	1,200	21	0	No
5	20	7	No	74	0	0	No
6	50	30	No	0	50	0	No

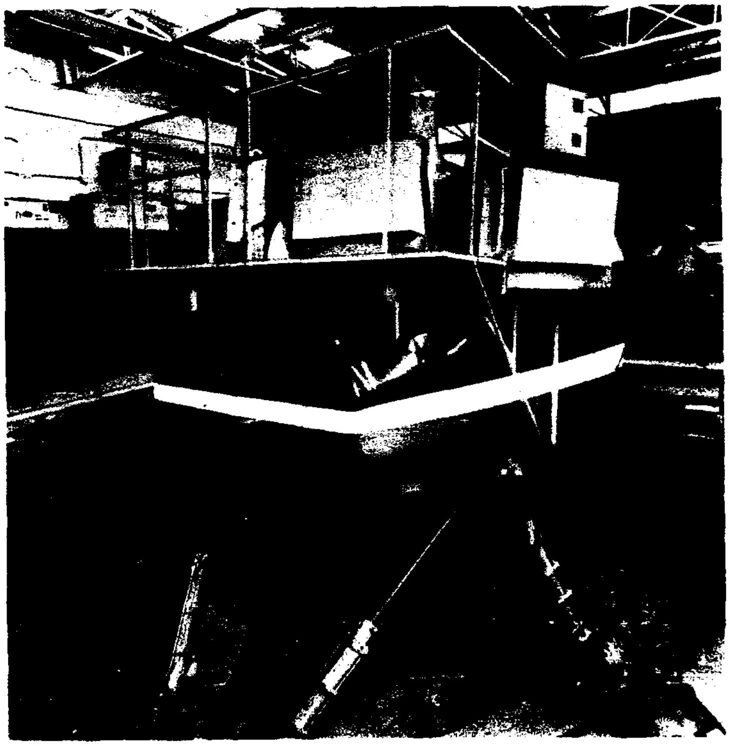


Figure 1 UTIAS Flight Research Simulator.

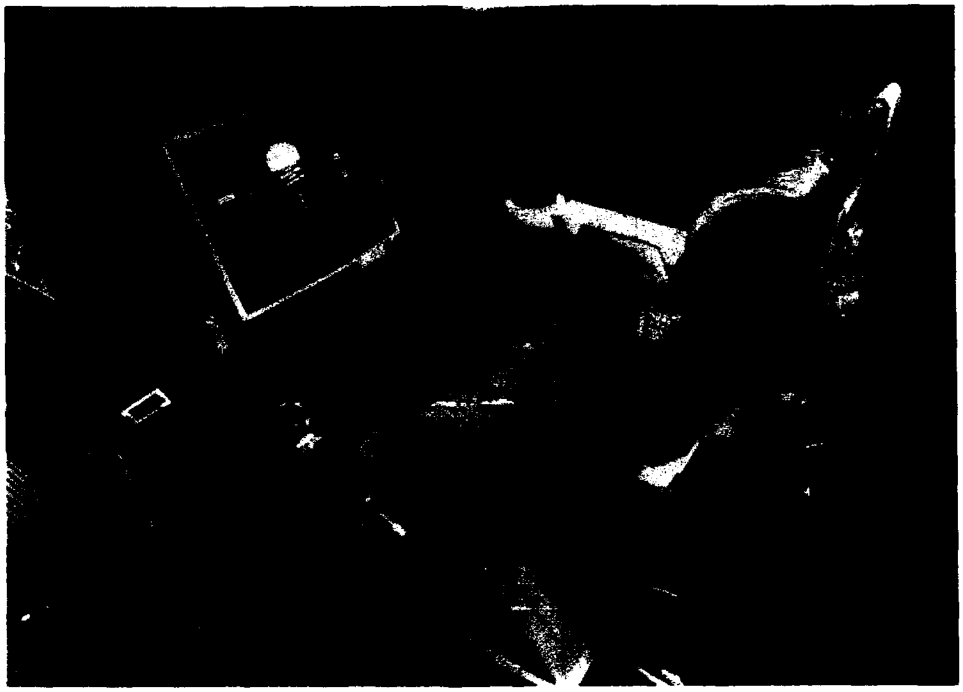


Figure 2 Helicopter Simulator Cockpit.

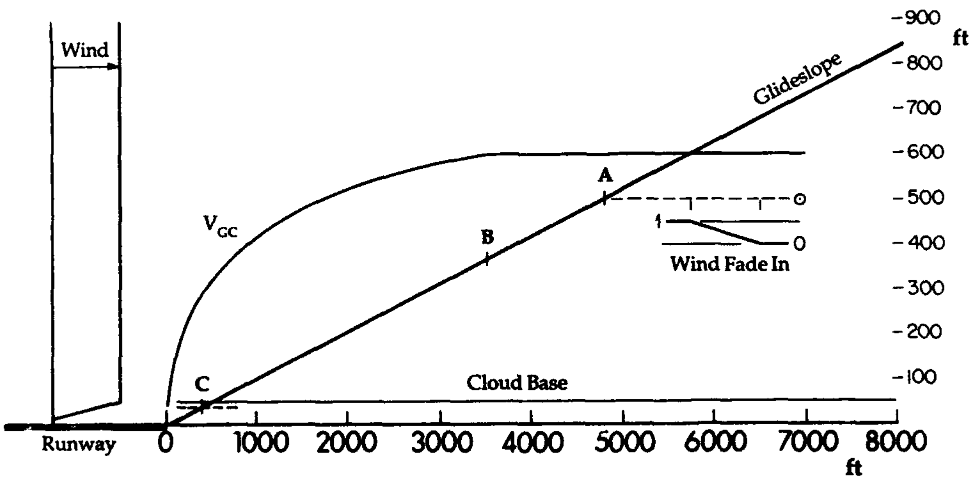


Figure 3 Landing Approach Details.

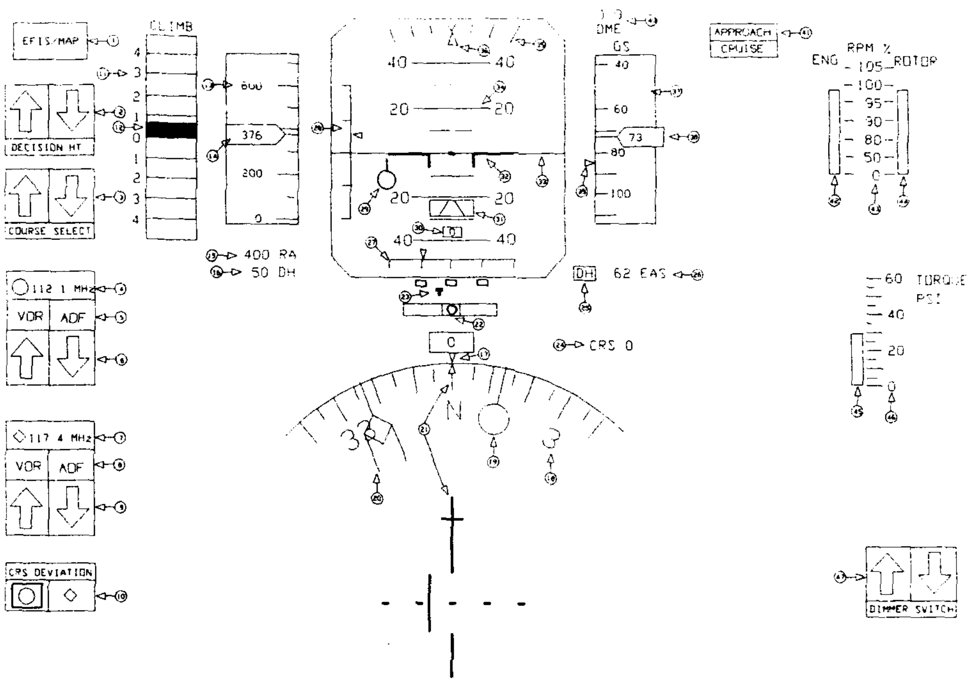


Figure 4 EFIS (see Reference 5 for details).

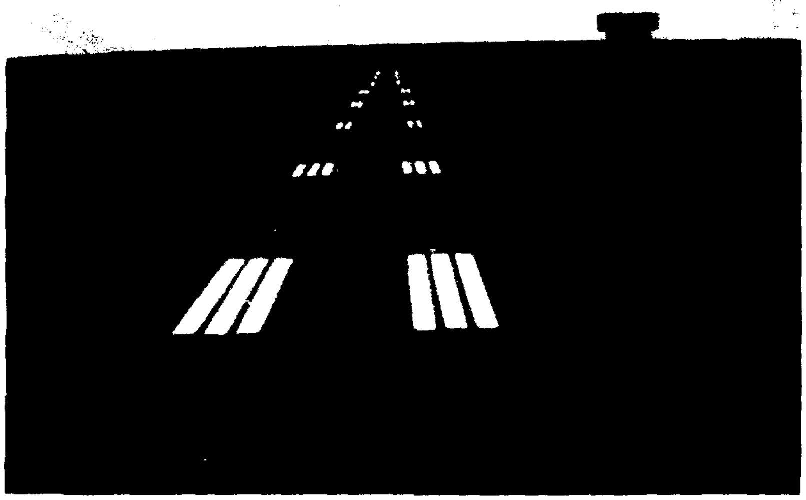


Figure 5 Airport Scene.

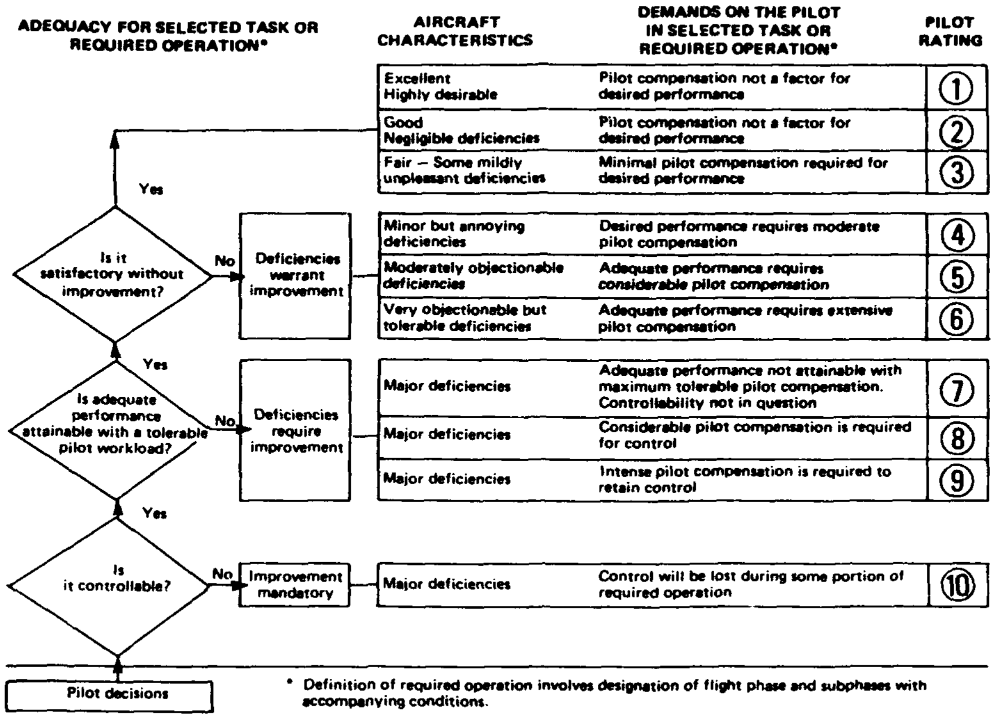


Figure 6 Handling Qualities Rating Scale.

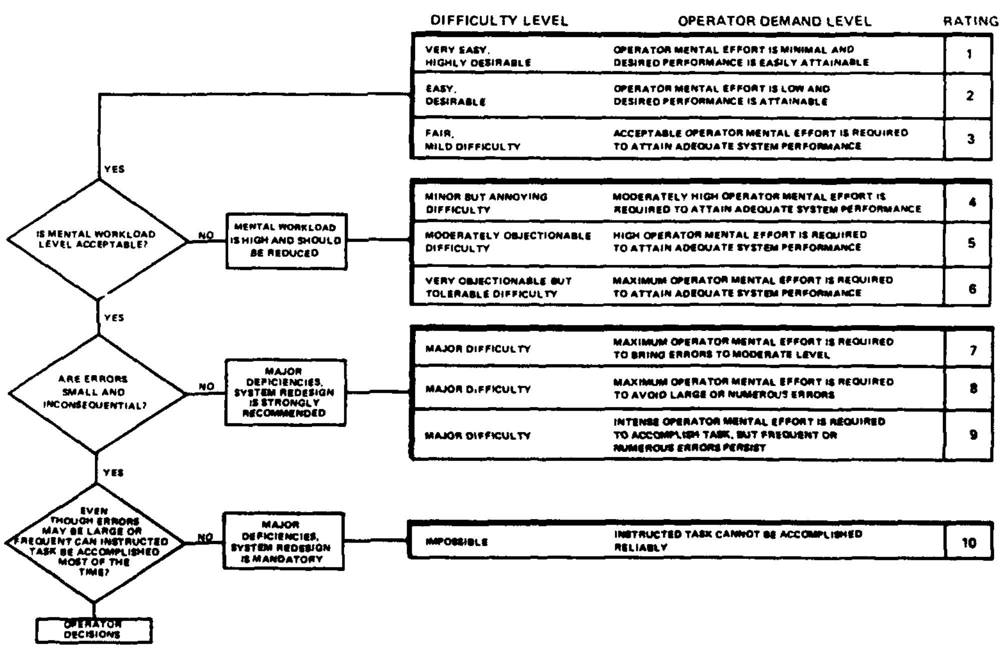


Figure 7 Workload Rating Scale.

BASED ON YOUR SHORT EVALUATION, IN WHICH OF THE FOLLOWING CATEGORIES WOULD YOU PLACE THIS CONFIGURATION:

1. The helicopter has good flying qualities and could be operated safely in a high-density IFR environment by one pilot without the assistance of additional crew members. ☐

2. The helicopter has marginal flying qualities for operations in a high-density IFR environment by one pilot without the assistance of additional crew members. ☐

3. The helicopter has flying qualities deficiencies which make it unsuitable for single-pilot operations in a high-density IFR environment, however it could be operated safely within such an environment if the pilot-in-command were relieved of all non-control tasks by an additional qualified crew member. ☐

4. The helicopter has major flying qualities deficiencies which make it unsuitable for operation within a high-density IFR environment. ☐

Figure 8 IFR Certification Assessment.

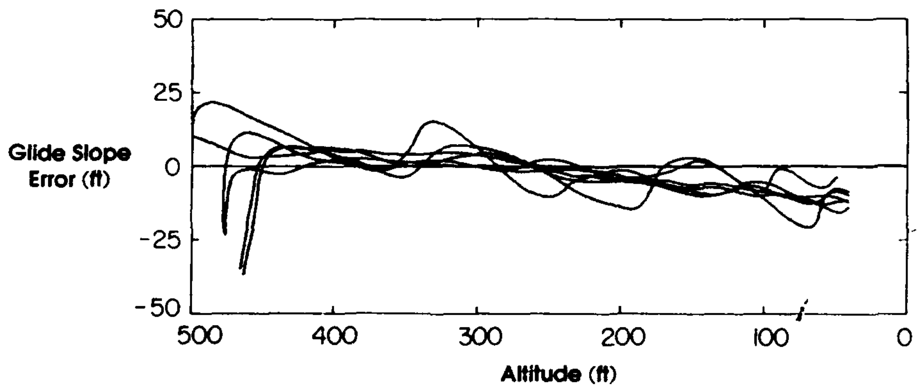


Figure 9 C3 Glide Slope Error vs. Altitude (Present Study).

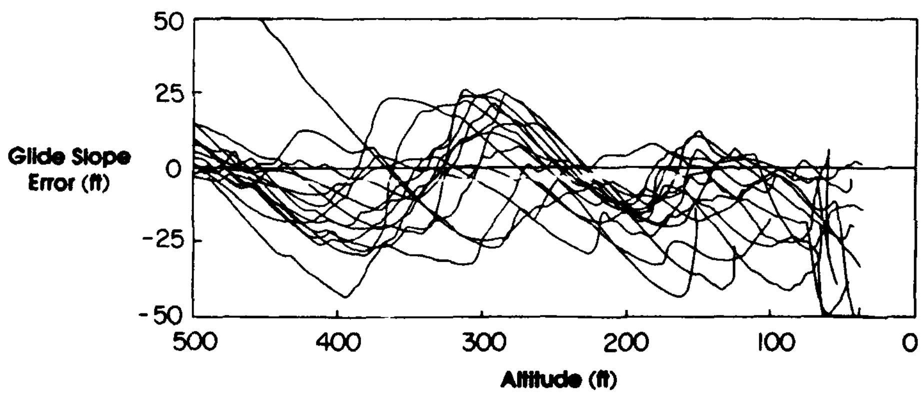


Figure 10 C3 Glide Slope Error vs. Altitude (Reference 9).

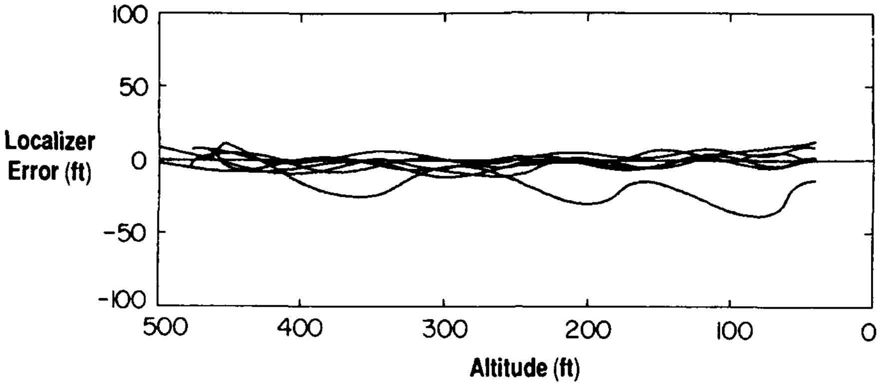


Figure 11 C3 Localizer Error vs. Altitude (Present Study).

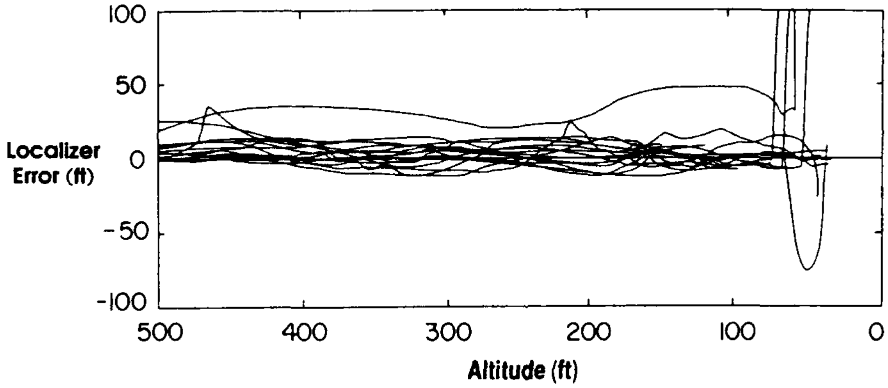


Figure 12 C3 Localizer Error vs. Altitude (Reference 9).

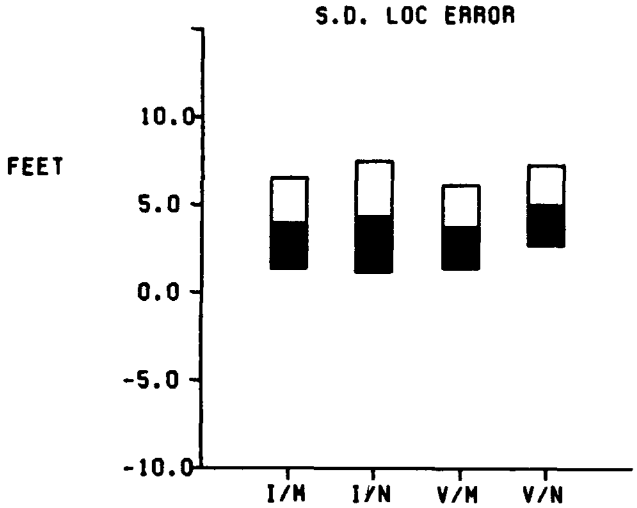
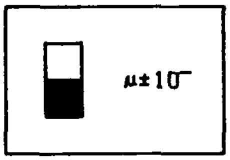


Figure 13 C1 Standard Deviation of Localizer Error.



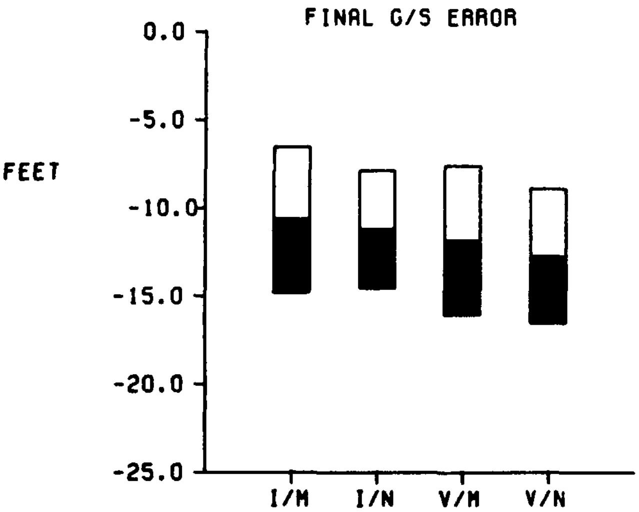


Figure 14 C1 Final Glide Slope Error.

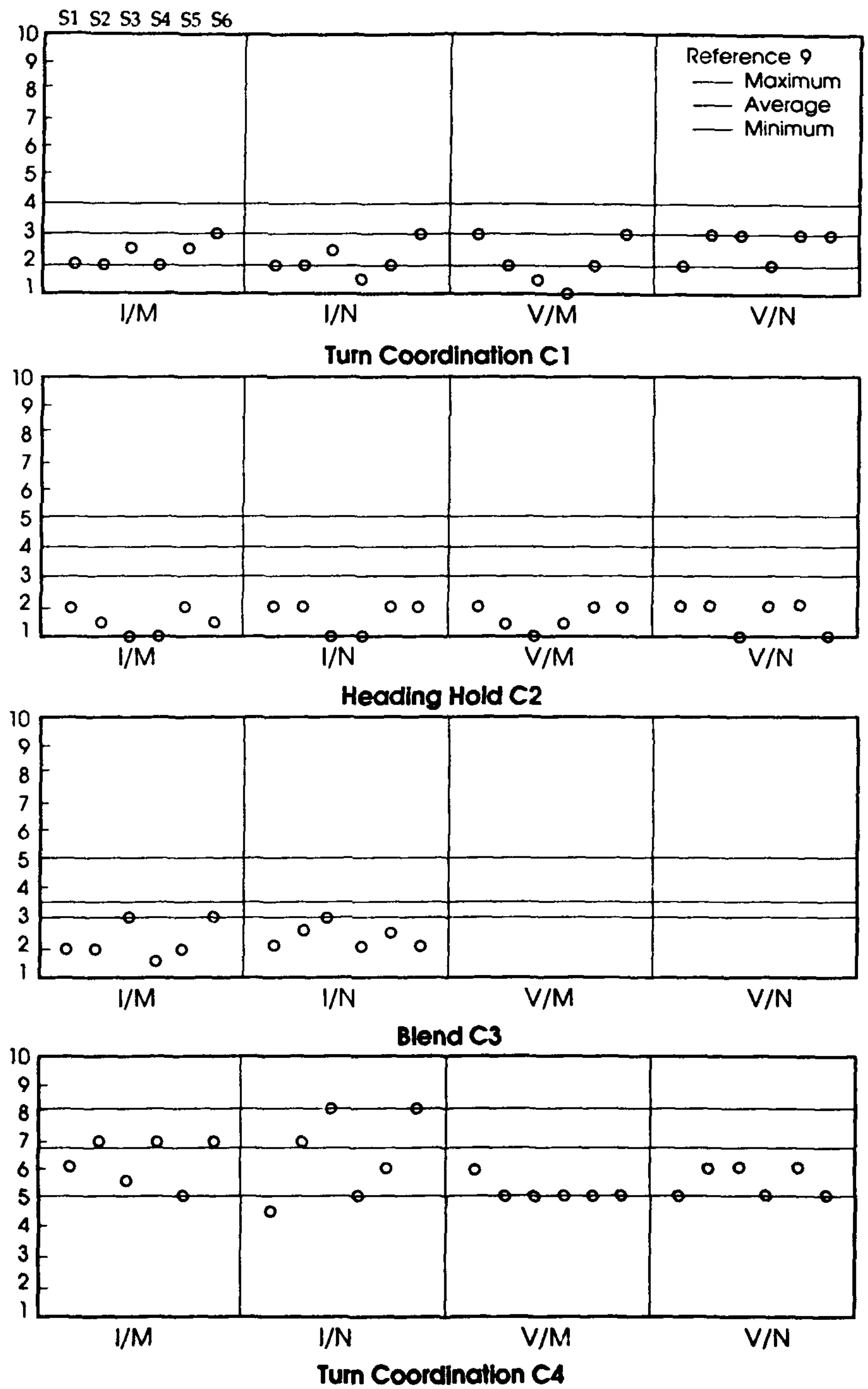


Figure 15 Handling Qualities Ratings.

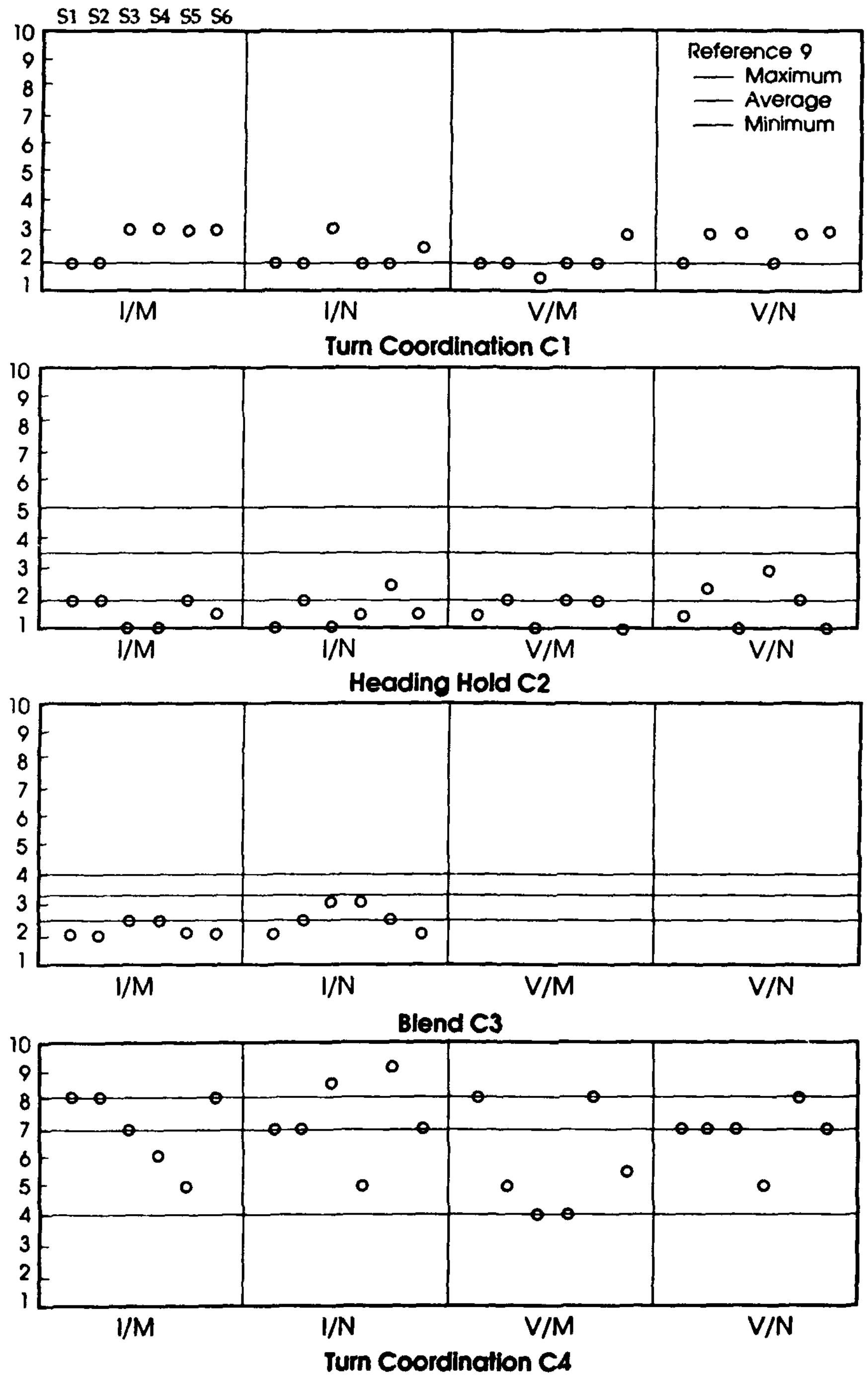


Figure 16 Workload Ratings.

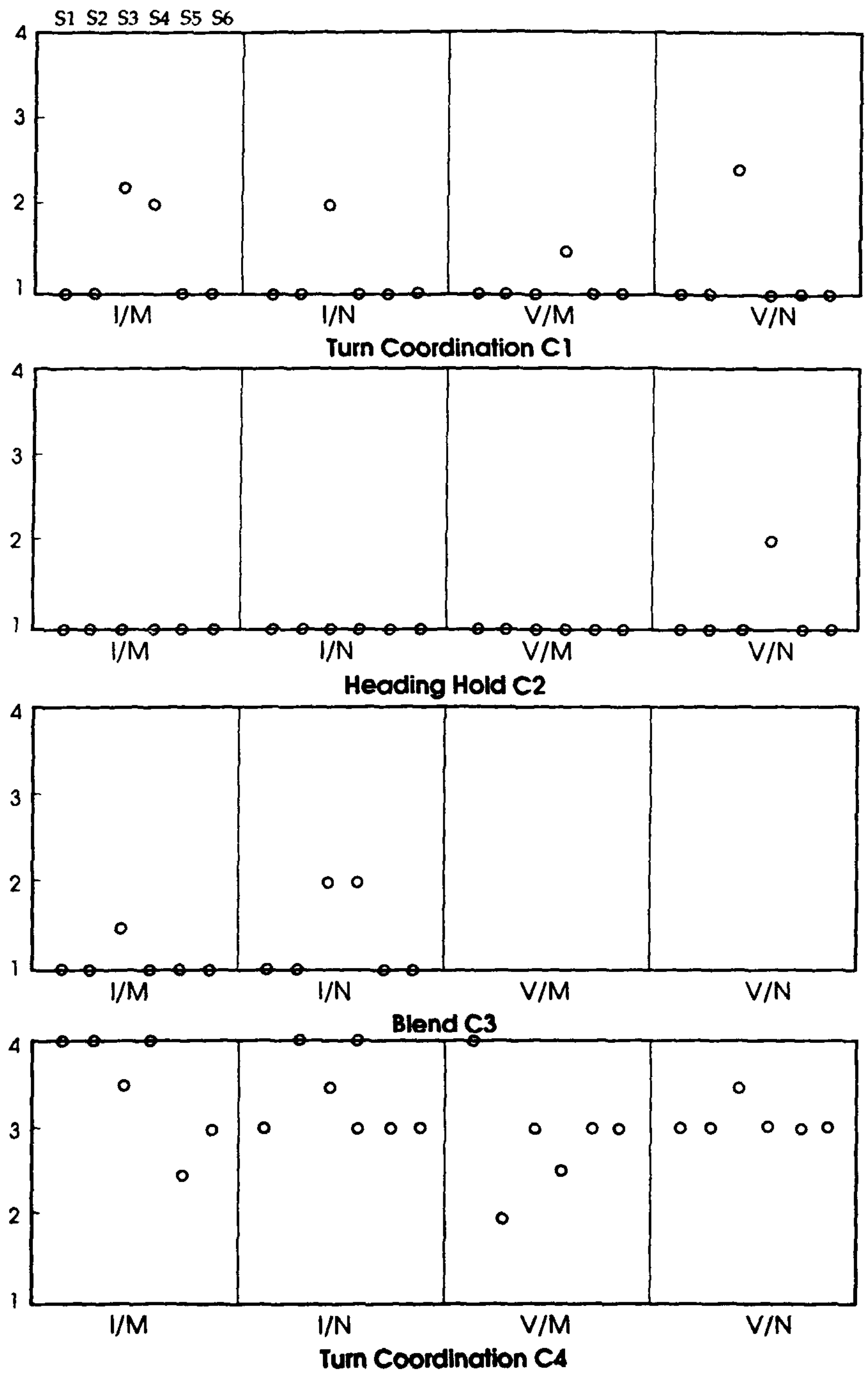


Figure 17 IFR Certification Assessments.

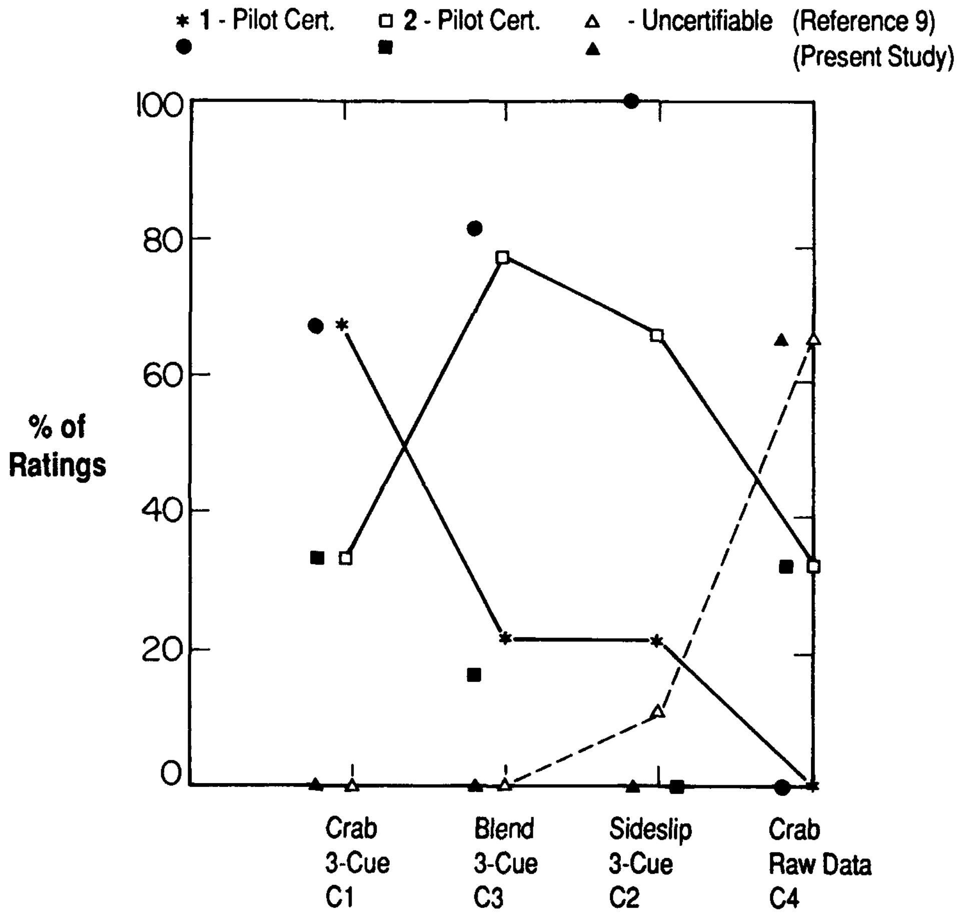


Figure 18 IFR Certification Assessment Comparisons (I/M Case).

APPLICATION OF PILOTED SIMULATION TO HIGH-ANGLE-OF-ATTACK FLIGHT-DYNAMICS RESEARCH FOR FIGHTER AIRCRAFT

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SUMMARY

This paper reviews the use of piloted simulation at Langley Research Center as part of the NASA High-Angle-of-Attack Technology Program (HATP), which was created to provide concepts and methods for the design of advanced fighter aircraft. A major research activity within this program is the development of the design processes required to take advantage of the benefits of advanced control concepts for high-angle-of-attack agility. Fundamental methodologies associated with the effective use of piloted simulation for this research are described, particularly those relating to the test techniques, validation of the test results, and design guideline/criteria development.

NOMENCLATURE

b	wing span, ft
C_l	rolling moment coefficient
C_m	static pitching moment coefficient
C_{m_q}	pitch damping coefficient
C_m^*	minimum nose-down pitching moment coefficient at any α
C_n	yawing moment coefficient
h	altitude, ft
M	Mach number
p,q,r	body-axis roll, pitch, and yaw rates, deg/sec
$\hat{p},\hat{r}$	non-dimensional body-axis roll and yaw rates, $\frac{pb}{2V}$ or $\frac{rb}{2V}$
p_w	wind-axis roll rate, deg/sec
q	pitch acceleration, rad/sec^2
S1, S2	slope of C_m versus α curve for α below and above $\Delta\alpha^*$, respectively, per deg
t	time, sec
$t\,\lvert\Delta\phi\rvert$	time to roll through a bank angle change, sec
T/W	thrust-to-weight ratio
V	free-stream velocity, ft/sec
X,Y	airplane body axes
α	angle of attack, deg
α^*	maximum α at which C_m^* occurs, deg
$\Delta\alpha^*$	range of angle of attack over which C_m^* occurs, deg
β	angle of sideslip, deg
γ	velocity vector pitch angle from horizontal, deg
δ_a	differential aileron deflection, positive for left roll, deg
δ_r	rudder deflection, positive for left yaw, deg
ε	tracking error, deg
θ,ϕ	pitch and roll angles, deg
$\Delta\phi_w$	change in wind-axis roll angle, deg
Ω	angular rotation rate, deg/sec

Subscripts:

max	maximum value
o	initial value
rec	value for recovery to low angles of attack

1 INTRODUCTION

Projected scenarios for future air combat indicate the need for highly agile fighter aircraft that can operate effectively over a substantially expanded maneuvering envelope beyond that of current fighters. It is expected that short-range air combat considerations will be dominated by the "all-aspect" capability of short-range missiles and guns. An essential requirement will therefore be to maneuver into a successful firing position as quickly as possible before the opponent can do the same. A number of piloted simulation and analytical studies (refs. 1-5) have shown that rapid, controlled maneuvering at high angles of attack is a key element for meeting this requirement. In response to this requirement, significant activities are currently underway to develop technologies that are needed to provide this enhanced capability. These technology areas include high-angle-of-attack aerodynamics, high-angle-of-attack controls, propulsion systems, pilot/vehicle interface, and weapons. The National Aeronautics and Space Administration (NASA) is actively engaged in these efforts, with a major goal of developing flight-dynamics technology to provide enhanced agility and handling qualities at high angles of attack that will enable aircraft to perform maneuvers that can be very advantageous in air combat.

Figure 1 shows two fundamental maneuvering advantages offered by this enhanced capability. The first involves rapid, large-amplitude rotation of the nose of the aircraft with relatively little change in the flight path. This type of motion can be produced by pure pitch or yaw maneuvers or by rolling about the velocity vector at high angles of attack.

This nose-pointing capability enhances target acquisition for weapons launch and quick recovery to conditions for engagement of another opponent, which is critical in a multi-aircraft combat situation. A second benefit of enhanced high-angle-of-attack maneuvering is the performance of rapid, small radius turns to gain a positional advantage. The use of post-stall angles of attack and very low airspeed conditions enables this repositioning capability. These capabilities can be achieved through the use of advanced control concepts such as vectoring of the engine thrust and unconventional aerodynamic devices that provide significant improvements in effectiveness, especially at high angles of attack.

A key NASA program which was conceived to address these advanced technology opportunities for high-performance aircraft is the High-Angle-of-Attack Technology Program (HATP). The HATP is a fighter technology development and validation program which is focusing on providing flight-validated methods and concepts essential for the design of fighters possessing unprecedented high-angle-of-attack maneuverability and controllability. The program uses the unique expertise and facilities of NASA's aeronautics research centers, including the Langley, Ames, and Lewis Centers. The research approach being taken is a balanced one involving closely-integrated wind-tunnel experiments, computational aerodynamics, piloted simulation, and flight tests of an F-18 research testbed airplane known as the High-Angle-of-Attack Research Vehicle (HARV). This vehicle has been modified to make it capable of testing advanced controls, including multi-axis thrust-vectoring and advanced aerodynamic controls. Reference 6 contains a more complete description of this program.

Piloted simulation has been an integral and key element of high-performance aircraft high-angle-of-attack flight-dynamics research at NASA-Langley for the past 20 years. A variety of studies have been conducted involving 11 aircraft configurations. These studies have included evaluations of advanced aircraft designs, investigations of new concepts such as advanced control effectors, and control law development work. Recent research activities have addressed flying qualities, control system design and effects, design guidelines development, and pilot/vehicle interface. The primary objectives of these simulator studies are to: (1) define and quantify the enhancements in agility provided by advanced control concepts under realistic combat conditions, (2) develop agility/handling qualities design requirements, including tradeoffs, for control laws, control effectiveness, and cockpit information systems, and (3) develop the design tools and methodology to enable these requirements to be met, so that the enhanced high-angle-of-attack capabilities can be effectively exploited.

Piloted simulation studies at Langley have been strongly linked with full-scale flight tests for nine aircraft, and these flight results have validated the simulation study approach. As a result, piloted simulation is playing a major role as a research tool for developing design methodologies in the high-angle-of-attack technology development process in the NASA High-Angle-of-Attack Technology Program. The primary facility used for this piloted simulation research is the Langley Differential Maneuvering Simulator (DMS), a fixed-based simulator which has the capability of simultaneously simulating two airplanes as they maneuver with respect to one another. The capability to simulate one-versus-two air combat is also provided by the use of a smaller dome facility known as the General Purpose Fighter Simulator (GPFS) in conjunction with the two DMS domes, as shown in figure 2. This piloted simulation agility research is illustrated in figure 3.

This paper presents an overview of the use of piloted simulation at NASA Langley for the development of high-angle-of-attack technologies as part of the NASA HATP program. The following sections describe the simulation methodologies used in the conduct of the tests, the validation of the test results, and specific methods used for design guideline/criteria development. Example results from recent research using piloted simulation are presented when appropriate to illustrate the use of these methodologies. Some of these examples are drawn from agility research which was conducted to investigate the use of a preliminary thrust-vectoring concept for the F-18 HARV (ref. 7). Other examples are from a generic program conducted jointly by NASA and the U.S. Navy in which candidate design guidelines for nose-down pitch control margin for relaxed-static stability combat aircraft were developed. This pitch control margin research is described in reference 8.

2 TEST TECHNIQUES

Overall Research Process

The overall approach used to conduct piloted simulation studies is illustrated in figure 4. This approach follows a logical progression from the generation of aerodynamic data using wind-tunnel tests to the final product of flight-validated results. The application of piloted simulation to flight-dynamics studies is, of course, dependent on the development of a valid mathematical model which generates accurate flight motions and handling qualities. Data obtained in static and dynamic wind-tunnel tests are used to develop aerodynamic math models for the studies. Although these tests provide much information on high-angle-of-attack characteristics, they do not allow for a quantitative pilot evaluation of the flying qualities of the full-scale airplane during representative air combat maneuvering. Using the math model data, analysis can be performed prior to the piloted evaluation to characterize the aircraft stability characteristics and maneuvering capabilities as an aid in the interpretation of the results. The simulation validation process involves the use of ground-based testing and correlation with full-scale flight tests. Once the simulation fidelity has been established the piloted evaluation can proceed with added confidence. If appropriate flight test results are available they can be used as an aid in the evaluation process to determine the suitability of the evaluation maneuvers and other aspects of the evaluation methodology. As preparation for flight tests, piloted simulation is extremely useful for developing appropriate maneuvers and providing pilots the opportunity to practice the required maneuver techniques prior to flight. The following sections will include descriptions of the simulation techniques and methodologies associated with the math model formulation, the evaluation of the simulation fidelity, the research evaluation, and validation using full-scale flight tests.

Simulator Capabilities

The use of piloted simulation at Langley for high-angle-of-attack studies evolved from the initial use of a simple, single cockpit with a limited visual display (the GPFS) to the present twin-dome DMS. Early simulation efforts with the

simple hardware identified several important simulator characteristics. Results of these studies indicated that in order to obtain a realistic evaluation of high-angle-of-attack flight characteristics, the simulation must present the pilot with a realistic air-combat-maneuvering environment. By providing a wide-angle visual display, air combat engagements could be simulated which required the pilot to be almost constantly looking outside of the cockpit to acquire and maneuver against an adversary; therefore, his opinion of the flying qualities and maneuvering capability would be based on similar visual information as in flight. In addition, it was found that there must be provided a good simulation of the cockpit environment in terms of pilot visibility, the display of flight instruments, and the use of a realistic force-feel system for the pilot stick and rudder pedals. Reference 9 describes some of these early piloted simulation studies.

As the simulation work at Langley progressed, the DMS was employed to meet these required characteristics. Unlike many other domed facilities, it is used exclusively for research, and has been used extensively for flight-dynamics research and air combat studies. The DMS is a twin-dome fixed-base simulator with many state-of-the-art features which enhance its utility as a research tool. It has a number of capabilities which provide a realistic maneuvering environment for the pilot and allow for flexibility and repeatability of maneuvering conditions, and it has other capabilities which are necessary for high-angle-of-attack research. A computer-generated imaging (CGI) system provides a high-definition wide-angle visual scene with rotational and translational cues for the pilot. Fully-programmable CRT displays and a head-up display (HUD) provide information within the cockpit, as shown in figure 5. One-versus-one air combat engagements can be simulated by using both DMS domes, and one-versus-two capability is also available by using the third, smaller GPFS dome. As many as two target images can be provided for each of the three domes using laser-generated or airplane model images with the proper apparent size, location, and orientation. The cockpits are equipped with a conventional center stick, rudder pedals, and a throttle. Provisions can be made for other pilot controls if required. A hydraulic force-feel system provides desired stick and pedal force and dynamic characteristics. Reference 10 contains a detailed description of the DMS.

Software Requirements

Aerodynamic Math Model. - In the development of a valid mathematical model for high-angle-of-attack simulation studies of specific configurations, sufficiently accurate models of the engine and flight control system are relatively easy to define. The ability to accurately predict high-angle-of-attack motions such as those shown in figure 1, however, is also highly dependent on the accuracy of the math model used to represent the aerodynamics during complex maneuvering. The aerodynamic modeling is the most difficult aspect of the high-angle-of-attack math model development, due to the extremely complex nature and configuration dependence of the flow phenomena at conditions beyond the conventional flight envelope. Comprehensive, non-linear data bases are required to accurately represent these high-angle-of-attack aerodynamic characteristic.. A major concern is that the mathematical modeling for the prediction of these motions is highly dependent on the results of wind-tunnel tests for the required static and dynamic aerodynamic data. The aerodynamic modeling accuracy will therefore only be as good as the accuracy of the wind-tunnel results and the accuracy of the application of these results to the math model.

In the past, conventional math models incorporating extensive data bases which combine static and small-amplitude damping wind-tunnel results have been applied with some success due to the fact that the simulated aircraft were quite limited in their ability to maneuver at stall/post-stall angles of attack because of poor control effectiveness (refs. 11 and 12). It is projected that technologies currently being explored will enable future fighters to have a greatly expanded high-angle-of-attack maneuvering envelope. Furthermore, these aircraft will have the capability of generating rapid angular motions throughout this enlarged envelope. Figure 6 conceptually illustrates the anticipated increases in maximum pitch- and roll-rate capability in an expanded angle-of-attack envelope. The ability to accurately predict these motions using mathematical models presents a most difficult challenge for the flight dynamicist. For these highly agile combat aircraft, recent results have shown that conventional aerodynamic math models may be deficient in correctly representing these aerodynamics. In particular, certain phenomena such as wing rock are not yet understood well enough to be modeled with high accuracy. The impact of incorporating additional terms in the modeling of high-angle-of-attack aerodynamics is being investigated. Examples of these terms include those which account for dynamic stall phenomena during pitch maneuvers and those which represent the effects due to steady rotational motions about the velocity vector (rotary derivatives) and lateral accelerations ($\dot{\beta}$ derivatives) during rolling conditions.

Large-amplitude aircraft maneuvers, however complex, can essentially be broken down into combinations of simple characteristic maneuvers. As is illustrated in figure 7, three basic characteristic maneuvers are: (1) pure pitch motion about the aircraft Y axis, (2) a constant angle-of-attack roll about the velocity vector, and (3) a pure sideslip motion. The first two types of maneuvers are the focus of current modeling studies at Langley. Reference 13 describes these investigations. The ability to roll effectively at high angles of attack is of particular importance to combat aircraft. There is concern that conventional math models which represent the dynamic effects by linear derivatives may not adequately represent the aerodynamics associated with rapid, large-amplitude coning rolls at high angles of attack that future highly agile aircraft will be able to perform. As a first step in investigating potential refinements to the aerodynamic math models, incorporation of rotary balance wind-tunnel data was studied. Assessment of the potential effects of this model refinement was made by comparing calculated motions from a six-degree-of-freedom simulation using both types of aerodynamic models. The simulation was of a representative current fighter airplane for which static, forced-oscillation, and rotary balance wind-tunnel data had been obtained. Figure 8 compares the time history responses to a maximum pilot roll command at $\alpha_0 = 35°$ using the conventional model and the rotational model. The results show substantial differences in the time histories of aircraft maneuver states such as sideslip and angular rates as well as control deflections. These results suggest that refinements to the currently used conventional aerodynamic models may be necessary to more accurately predict the maneuver performance, stability, and controllability of future highly agile aircraft. The identification and implementation of appropriate refinements presents a major challenge for flight dynamicists. Methods to accurately apply wind-tunnel

results based on comparisons between simulation and flight motions are being investigated using techniques such as parameter identification, time history matching routines, and computational fluid dynamics.

Flexibility. - Another key software requirement for piloted simulation studies is flexibility in the model for the purpose of examining the effects of parametric variations of various aircraft characteristics. The math model and cockpit displays in the DMS are fully programmable, which make this facility uniquely suited for flight-dynamics research. Past simulation studies at Langley have involved the variation of performance, flight control law and control system characteristics, stability characteristics, and control effectiveness. Often, these variations can be easily implemented by assigning to a variable name a numerical value which can be changed at will. However, in some cases, multipliers or extrapolations which are functions of some variable or a completely different representation may be required. The purposes of these investigations have been to: (1) assess the effect of airframe and engine modifications and advanced control concepts on the stability characteristics and/or maneuvering performance, (2) develop flight control laws to effectively utilize high-angle-of-attack maneuvering capability, and (3) develop design criteria for control laws and control effectors. An example of a significant agility result obtained from a simple parametric variation is shown in figure 9. The sea-level static thrust-to-weight ratio of a configuration with thrust-vectoring (TV) controls was varied to evaluate the effect of thrust changes on the enhancements in maneuvering capability due to their use in rapid nose-up pitch maneuvers. A maximum pitch command was applied from 1g trim conditions at various angles of attack. The use of thrust-vectoring controls increased the maximum trim angle of attack from 55° (for the baseline configuration without thrust vectoring) to as high as 80°. The results were expressed in terms of the maximum pitch-rate achieved during these maneuvers, and showed that even configurations with conventional thrust-to-weight ratios of about .7 could realize substantial increases in pitch-rate capability over an expanded angle-of-attack range compared with the baseline configuration without thrust-vectoring controls.

Simulation Fidelity

Historically, high-angle-of-attack simulations on the DMS have correlated well with flight tests, especially with respect to the identification of flight-dynamics problems as well as airframe and flight control concepts to alleviate these problems. However, as was mentioned previously, the need for flight validation of the simulation fidelity has become apparent in recent airplane development efforts. In some aircraft programs significant discrepancies have been encountered between ground test facilities and between some ground test facilities and flight, as described in references 14 and 15. These experiences strongly suggest the need for flight validation to ensure confidence in ground-based results.

As was described previously, NASA is currently conducting full-scale flight tests of a research testbed F-18 known as the HARV, as part of the HATP program in which the use of advanced controls for agility research and control margin/control law design criteria development methods is being investigated. The HARV is uniquely suited for high-angle-of-attack flight validation activities, as it is equipped for the monitoring of more than 700 flight test parameters and the use of flow visualization techniques. This flight test program will be used as an example to illustrate the process of assuring simulation fidelity. The approach to flight testing the HARV equipped with thrust-vectoring controls will be similar to other high-angle-of-attack flight tests which have been conducted. This approach includes updating the aerodynamic data base so that it consists of the best currently known information about the aerodynamics of the vehicle in order to validate the ability of ground-based simulations to predict reliably the dynamic response of the airplane to any pilot inputs. As flight data are becoming available at high angles of attack, parameter estimation efforts are under way to refine the aerodynamic data base for the HARV. An important research objective of the HATP program is the improved modeling of aircraft dynamics at large angles of attack and sideslip, as was previously described.

One method of correlating large-amplitude simulation and flight motions is to compare numerical values of various parameters associated with such maneuvers. An example of this correlation between simulation and flight results for the HARV (without thrust-vectoring controls) is shown in figure 10. Shown is the time to roll through a bank angle change of 90° and the maximum roll rate achieved, starting from wings-level 1g trimmed flight and from M = 0.6 (accelerated conditions) with an initial bank angle of about 90°, versus angle of attack. Results for several maximum-command roll maneuvers performed in flight tests are compared with the results obtained in the DMS simulation. These particular results indicate good correlation between simulation and flight, so that no modifications to the simulation math model are indicated. However, if such results show a significant difference between simulation and flight, then corrections should be applied to the math model. Additional correlation efforts are continuing at NASA which involve the use of parameter estimation techniques and non-real-time (batch) computer routines which use the recorded pilot control inputs or control surface deflections from flight to generate the resulting motions predicted by the simulation math model.

Evaluation Maneuvers

A fundamental test technique for high-angle-of-attack piloted simulation studies is the systematic progression, in distinct phases, from the performance of "open-loop" (i.e. pilot in the loop performing simple inputs) maneuvers to one-versus-one air combat, to one-versus-two engagements. Normally the first phase of an evaluation of a particular configuration with advanced controls involves pilot familiarization with the simulated airplane, evaluation of the high-angle-of-attack maneuvering characteristics of the airplane, and development of closed-loop and air combat maneuvering tasks for use in the next phase of the study. For studies to develop control margin design criteria, the primary evaluation maneuvers may be very few and "open loop", in order to focus on specific response characteristics for various levels of control effectiveness and to remove as many control system effects as possible. Pilot familiarization of each configuration in such a study can be relatively brief.

The second phase of these piloted evaluations involves having the pilots fly the simulated airplane in closed-loop maneuvers. These maneuvers may involve the capture of a specific flight condition, flying against repeatable recorded air combat tasks, or engagements against a pilot in the second DMS dome. For agility research, this phase of the evaluation serves the purpose of quantifying the

maneuvering benefits of advanced controls in realistic one-versus-one air combat situations and to uncover any handling qualities considerations or airframe/control system deficiencies which should be corrected. Agility and handling qualities research are closely related, as effective use of enhanced agility must be accompanied by acceptable handling qualities. Examples of studies which have specifically addressed handling qualities requirements at high angles of attack are described in reference 16. For control margin design criteria development, the performance of closed-loop and complex air combat maneuvering serves to validate or define any adjustments/refinements to the design criteria developed in the "open-loop" primary evaluation. The definition of control margin, agility, and handling qualities requirements determines the fundamental control law characteristics for enabling these requirements to be met. Unfortunately, a systematic, proven set of design guidelines and methodologies for the high-angle-of-attack control system development process to maximize agility and fully exploit high-angle-of-attack maneuvering capability does not yet exist. The HATP program is addressing this need.

Agility characteristics and design criteria must be evaluated under the most real-world conditions so that the complex maneuvers can be performed in rapid succession and the pilot's attention must be divided between flying the maneuvers, keeping track of a target, and managing a weapon system. Piloted simulation studies of one-versus-one air combat with one configuration having enhanced high-angle-of-attack agility and the other being a conventional fighter have been conducted for this purpose (refs. 1 and 2). Results from these investigations have shown large benefits from the use of high-angle-of-attack agility. They have also quantified to some extent the level of benefit obtained from given amounts of control margin augmentation. The significant advantages seen in one-versus-one scenarios often come from the use of very high-angle-of-attack and low airspeed maneuvers. In an m-versus-n environment the level of augmentation required to obtain a significant advantage may be higher, and energy management will increase in importance. The next step in investigating high-angle-of-attack agility and design requirements is the simulation of one-versus-two engagements in which one highly agile vehicle engages two conventional configurations. The Highly Agile Vehicle Versus Two (HAVV TWO) program is currently under way at Langley to identify and evaluate additional considerations which the multi-bogie environment places on control effectiveness requirements and pilot situational-awareness needs. Some early results from this study are described in reference 3. This study began with very simple engagements and is progressing towards more complex engagements in order to enable quantification of the exchange ratio improvements due to enhanced agility and identification of the configuration characteristics that played a significant role in producing the improvements.

An important requirement for evaluation maneuvers used in piloted simulation studies is that they should relate as directly as possible to the airplane characteristics being evaluated, so that the pilot comments and ratings are meaningful and so that the quantitative results can be used as directly as possible. The maneuvers should be performed in a manner which insures that the critical flight conditions, pilot techniques, and resulting aircraft motions are examined. As was discussed previously, two significant high-angle-of-attack large-amplitude maneuvers are pure pitch maneuvers and rolls about the velocity vector. For high-angle-of-attack agility/advanced controls research, then, maneuvers which involve full pilot inputs in pitch and roll should be performed over the angle-of-attack and speed envelope of interest. The maneuvers should fully define the limits of the enhanced maneuvering envelope and agility/handling qualities design requirements and tradeoffs. These maneuvering characteristics can be defined by analyzing maneuvers in which the pilot inputs are held until the maximum maneuvering rates are attained and those which involve closed-loop captures of specific conditions. These types of maneuvers should be performed in non-combat situations (for ease of analysis) as well as in tasks involving repeatable targets and in simulated air combat engagements. This approach also helps to identify any weaknesses or deficiencies in the control law design being used.

As was mentioned previously, for some simulation research only one "open-loop" primary evaluation maneuver may be required. For control margin design criteria development, this approach allows many parametric variations of control effectiveness to be made and evaluated by several pilots. The initial conditions for evaluation maneuvers must also be carefully considered. For example, maneuvers used in the evaluation of control margin requirements, of which pilot ratings and comments on aircraft response may be an integral part, should be designed so that the motions that the pilot observes visually are generated as much as possible only by the control moment capability of the airplane. Unrelated or secondary motions such as those due to control system effects, thrust or other performance characteristics, or kinematic and other coupling motions should be minimized. By initiating such maneuvers at 1g stabilized trim conditions, at which there are no net forces or moments acting on the airplane such that $q = \dot{\alpha} = \dot{\gamma} = \ddot{h} = 0$, the thrust/performance effects are minimized. Figure 11 depicts this flight condition. The flight path angle (γ) will be less than zero (descending flight) at angles of attack where there is insufficient thrust to maintain level flight. These maneuver conditions are ideal for directly assessing the control moment available at that angle of attack. The primary maneuver used in the evaluation of nose-down pitch control requirements was a pushover from these conditions at a high angle of attack to low angles of attack (ref. 8). A nose-down command applied at initial conditions at which the pitch attitude or the flight path angle is changing ($\dot{\theta}$ or $\dot{\gamma} \neq 0$) will result in changes in angle of attack that are not due solely to the nose-down moment generated by the application of nose-down controls. More complex maneuvering at a variety of flight conditions will be performed as part of the validation process in this study.

For purposes of quantifying and documenting the fundamental aircraft response characteristics and agility/maneuvering capabilities in a way which will be reproducible in flight tests for correlation with simulation results, the non-combat maneuvers performed in these evaluations should be repeatable and easily executable by the pilots. Maneuvers for which the initial conditions are dynamic (i.e. there are forces or moments acting on the airplane) will make the maneuver less repeatable, and will add complexity to the pilot technique if the timing of the pilot input is to be made at a specified point during the changing conditions. Pilot technique complexity is also increased if a sequence of inputs is required. Maximizing the repeatability and ease of execution of the maneuvers also minimizes difficulties in analyzing the results and comparing the results with full-scale flight motions. For closed-loop maneuvers in

which flight conditions are captured within specified tolerances, these tolerances need to be tight enough to give meaning to the results and yet not so tight that they cannot be met in simulation and flight tests. In the progression from "open-loop" to closed-loop to air combat maneuvering, the repeatability and ease of pilot technique naturally decreases; however, by first obtaining a fundamental understanding of the results from simpler maneuvering, the analysis of more complex maneuvering will be simplified.

Role of Simulator Pilots in Evaluations

There are several factors which influence the effective use of research pilots for high-angle-of-attack simulation studies: (1) the number of participants and their backgrounds, (2) their involvement in the research process, (3) the establishment of their learning curves, (4) their acclimation to high-angle-of-attack motions, and (5) the approach taken to pilot ratings and comments.

It is highly desirable to use several research test pilots in these studies in order to assure that the results will be generally applicable, particularly in studies involving the use of pilot ratings. They should ideally have extensive flight testing background and come from a variety of sources, including the military and industry. They should be familiar with air combat maneuvers, tactics, and weapons systems employed with current fighter airplanes, and should be involved throughout the program. Any pilots who are involved in full-scale flight tests of a specific test configuration associated with the study will need to fly the simulator to obtain information prior to the test flights or to validate the simulation results if test flights have already been made.

Pilot involvement in the research process should begin with a thorough briefing regarding the background and purpose of the program and the simulator characteristics, if they are not familiar with them. They should be involved as much as possible in the development of the test techniques and the methodology to be used in the study, including the maneuvering techniques, rating approaches, and the determination of figures of merit.

An important aspect of the assessment method is the establishment of the learning curve before pilot comments are expressed or ratings are given. For simple, highly repeatable tasks, a particular configuration or parametric variation may be evaluated with very few runs; however, for more complex tasks in which the motions may vary due to the use of different pilot techniques, a number of runs may be required to establish the learning curve.

The performance of maneuvers at high angles of attack can produce unconventional motions which affect the pilot's perception of aircraft responses to his inputs. A primary example of this motion is the change in the aircraft's lateral-directional response to roll inputs at increasing angles of attack. Lateral inputs at high angles of attack to command a coordinated roll about the velocity vector produce an increasing proportion of body axis yaw rate compared with roll rate as the angle of attack is increased. When first encountered, this yawing motion can be disorienting or can appear to be a departure from controlled flight. Additional simulation time may be required for pilots to become acclimated to it. This phenomenon will be discussed further in a later section.

For some research in which specific pilot ratings are required in order to quantitatively document the pilot's opinion of an aircraft characteristic, existing accepted rating scales such as the Cooper-Harper handling qualities rating scale (see figure 12 and reference 17) may not be appropriate. A new rating scale and/or rating approach may need to be developed. For instance, the Cooper-Harper scale is not applicable to piloted assessments of "open-loop" responses to simple inputs for which pilot compensation is not usually a factor, such as assessments of departure/spin recovery or rate capability. An example of a scale that was developed for the quantitative assessment of "open-loop" response to nose-down pitch commands for recovery from high angles of attack is shown in figure 13 and is described in reference 8. The evaluation pilots as well as the engineers and flying qualities specialists were actively involved in the development and refinement of this scale, which has some structural similarity to the Cooper-Harper scale. In addition to the rating scale, a questionnaire which provided suggestions for qualitative pilot comments concerning additional pitch response characteristics and one which addressed the characteristics of the evaluation maneuvers were used and are shown in figures 14 and 15. These questionnaires were useful for generating additional pilot comments during the simulator sessions and debriefings. As a general practice for all piloted simulation studies, it has been found to be useful to obtain written summaries from pilots after each simulation session as further documentation and clarification of their evaluations. The information obtained from the pilots' ratings and comments enabled the definition of two primary levels of response, as shown in the figure. These levels were important for establishing design requirements based on safety of flight and tactical considerations.

Analysis of Results

The overall results of piloted simulation studies are generally derived from the analysis of aircraft motions and controls, pilot qualitative comments concerning workload and aircraft response, and quantitative pilot ratings. When qualitative or quantitative pilot opinion is used to make comparisons of maneuvering capability at different flight conditions or between aircraft configurations, it is desirable for them to be involved in the analysis process as much as possible in order to aid in the definition of the figures of merit which most influenced their opinions. The results should be expressed in terms of maneuvering performance and the effect of the variations which were made. For agility research, many figures of merit have been used and/or proposed to quantify the results of maneuvering capability. These figures of merit include the time to reach a flight condition or to capture it within a specified tolerance, and maximum angular changes, rates, or accelerations achieved during the maneuver. As yet, there is no generally accepted specific set of figures of merit (also referred to as metrics) for quantifying high-angle-of-attack agility. A sample presentation of the results for simulated "open-loop" roll maneuvers was shown in figure 10. The DMS results for the F-18 HARV with and without thrust-vectoring controls are shown in figure 16. The results show significant maneuvering improvements (shorter time to bank and increased roll rate) for the configuration with thrust vectoring. The two figures of merit used, though very simple, are clearly useful for quantifying enhanced roll agility, and are therefore useful for identifying the maneuvers which are most appropriate for agility evaluations. Such results can also be used to define control law design goals.

A number of ways to meaningfully quantify maneuvering enhancements in simulated air combat engagements also exist. In particular, such overall figures of merit as the angle (ε) between the aircraft X body axis and the range vector to the opponent and the rate of change of this angle indicate instantaneous maneuvering advantage. The time on advantage, defined as the cumulative time during which the aircraft $\varepsilon < 90°$ and the opponent's $\varepsilon > 90°$ is an indicator of sustained maneuvering advantage. The results as indicated by these and other measures of maneuvering advantages during air combat should be expected based on an understanding gained from earlier analysis of non-combat maneuvers. Of course, the victor in any air combat engagement will be the first one who satisfies the weapons firing/launching parameters, which normally involve ε, the range between aircraft, and other requirements. By performing sufficient numbers of engagements, a meaningful probability of a specific configuration being the victor against some other configuration can be determined. References 1 through 3 contain analyses of combat maneuvers and engagements for configurations with and without thrust-vectoring controls.

A particular data analysis process is appropriate for the determination of control margin design guidelines involving pilot ratings. The determination of appropriate candidate figures of merit for the analysis will be discussed in a later section; however, for each candidate figure of merit selected, the level of statistical correlation should be determined between the quantitative values achieved by the aircraft for that response characteristic and the pilot comments and ratings assigned. In this manner the most significant figure(s) of merit that best characterize those aspects of the response that the pilots evaluated can be determined. This process is depicted in figure 17. The statistical correlation method that was found to work well for the determination of the figures of merit for nose-down control response was to compute the mean values of the figure of merit versus pilot rating and the 95-percent confidence intervals about the mean at each rating value. For this study, one figure of merit that was determined by this analysis technique to be significant was the maximum nose-down pitch acceleration achieved within the first second of a full nose-down command at high angles of attack. These results are shown in figure 18. The clear dependence of pilot rating on the amount of pitch acceleration achieved and the generally small confidence intervals were evidence of a meaningful correlation. This information was then used in the determination of design criteria.

3 FLIGHT VALIDATION OF RESULTS

As was shown in figure 4, final determination of the results of high-angle-of-attack piloted simulation studies involves the use of ground-based testing and full-scale flight testing to validate the simulation results. These tests are used to determine any refinements needed to the simulation mathematical model or the evaluation methodology used, such as the maneuvers and rating approaches. The simulation also serves as a tool for flight test planning and practice for the test pilots. In flight tests, real-world considerations with respect to pilot/vehicle-interface needs can be evaluated and their effect on the validity of the simulation results assessed. These considerations include cockpit displays and controls as well as motion/physiological effects such as spatial disorientation and accelerations experienced by the pilot. The following sections will discuss the use of flight testing for the validation of simulation results.

Validation of Maneuvers and Rating Approaches

Considerations. - An evaluation of the maneuvers performed and the validity of the rating approaches used in the simulation studies must also be made in flight tests. It is important that the simulation results be based on realistic maneuvers that can be performed in flight within acceptable tolerances for the maneuver performance without violating any aircraft restrictions or requiring excessive pilot workload. As an example, during full-input large-amplitude rolls at high angles of attack, holding the angle of attack nearly constant during the maneuver can be a high workload task, both in simulation and flight tests. If an additional requirement such as capturing a roll angle is added, the workload may be unacceptably high, especially if the tolerances are tight and the handling qualities are poor. The simulation results should also accurately predict the pilot's qualitative opinion and numerical ratings in full-scale flight. If the pilot's opinion of the aircraft response is significantly affected in flight due to factors such as the effects of motion, the fixed-based simulation results will need to be modified. It may also be determined in flight tests that the pilot rating approach itself needs to be altered. Future flight tests of the HARV will yield such information concerning the validity of the nose-down control margin study conducted on the DMS and the application of the Cooper-Harper handling qualities rating scale to enhanced high-angle-of-attack flight.

Status of Maneuver Definition. - During flight test programs, as the airplane is cleared for different regions of the flight envelope from benign flight conditions to more demanding ones, maneuvers and tests performed during piloted simulation are repeated for evaluation/validation purposes. Accepted task performance guidelines for nonlinear piloted simulation of high-angle-of-attack maneuvering and corresponding evaluation procedures/guidelines for flight test do not currently exist. Historically, different ad hoc approaches have been used by various organizations during specific programs. However, little attempt has been made to pull together these various approaches and take advantage of the lessons learned over the years. Therefore, development of open- and closed-loop task performance guidelines and evaluation procedures that are generally accepted for agility research and control law evaluations is a current and future research challenge.

High-angle-of-attack research programs are attempting to address the issue of task definition. NASA has proposed that a set of standard, representative tasks be defined and used in all ongoing high-angle-of-attack research flight programs, with the same tasks being evaluated in simulation and flight. Still unresolved is what the specific tasks should be. Research activities are underway to develop and ultimately flight-validate candidate tasks. Starting with the fundamental characteristic maneuvers shown in figure 7 as a basis, a preliminary set of candidate maneuvers which could be used for high-angle-of-attack agility and control law design research is being evaluated using the DMS. A wide variety of maneuvers were initially considered on the basis of their potential for quantifying the enhancements in agility due to the use of advanced control effectors. Figure 19 describes the resulting candidate set of maneuvers, which is designed to evaluate the aircraft's ability to rapidly point the nose relative to the flight path, as depicted in figure 1, by pitching or rolling about the velocity vector. In addition to these nose-pointing maneuvers, others are being developed on the DMS which will demonstrate the second aspect of

agility shown in figure 1 -- the ability to reposition the aircraft by quickly turning the velocity vector. The DMS is also being used to develop flight test maneuvers based on the handling qualities evaluations described in reference 16. Flight tests of these various types of maneuvers using the F-18 HARV will validate their utility for high-angle-of-attack agility, handling qualities, and control law evaluations.

Pilot/Vehicle Interface Considerations

An important goal of the research within the HATP program is to define the considerations and needs of the pilot with respect to cockpit displays and controls, the possibility and consequences of spatial disorientation during maneuvers, and the severity and effect of g loads experienced by the pilot. Any or all of the potential difficulties associated with these factors can affect the validation of piloted simulation results because they can cause problems with the accuracy and repeatability of the test points.

The presentation of cockpit displays and the mechanization of the controls can affect both the pilot's ability to perform a maneuver and his opinion of the aircraft response. For example, if a display of critical information for performance of the maneuver is difficult to read because of its design or placement, the maneuver performance and/or pilot opinion may be affected. Because of the nature of high-angle-of-attack flight and potential problems with spatial disorientation, the performance of large-amplitude maneuvers at these conditions may require the use of unconventional displays. The DMS is being used to investigate the use of helmet-mounted displays with a view towards flight tests of such a system on the F-18 HARV.

Spatial disorientation, which can cause the maneuver performance to suffer due to a reduction in situational awareness, can result due to the occurrence of unusual flight attitudes or motions. Such disorientation can occur within the conventional flight envelope at angles of attack below the stall; however, the possibility exists, based on simulation experience, that more severe disorientation may result during the performance of maneuvers such as high-angle-of-attack rolls about the velocity vector. Pilots who are used to rolling about the longitudinal body axis at low angles of attack may become very disconcerted at first by the substantial initial yawing motion observed in response to a roll input. Pilots have adapted to this phenomenon in simulations; however, there is currently a lack of flight experience with these motions. Simulation results related to agility and design criteria development may have to be altered after comparing these results with flight test data. Applicable data should be available soon from the F-18 HARV flight tests and other high-angle-of-attack flight programs. This issue is also being addressed as part of the research being conducted with helmet-mounted displays mentioned previously.

A second physiological consideration for pilot/vehicle interfacing is the potential for excessive accelerations (g loads) encountered at the pilot station during rapid maneuvering at high angles of attack. The primary concerns are the onset rate of normal acceleration on the pilot during rapid pitch maneuvers, the buildup of axial acceleration ("eyeballs-out" g's) due to high yaw rates during high-angle-of-attack rolls, and the lateral accelerations experienced due to rapid yaw accelerations in these rolls. These values can be easily calculated from simulation data; however, only flight tests will determine exactly how the pilots will respond to these motions and how much they will affect the results of simulation studies.

4 CONSIDERATIONS FOR DESIGN CRITERIA DEVELOPMENT

The overall piloted simulation research process as shown in figure 4 is valid for design criteria development. However, for some types of research, it is appropriate to adapt or extend the general techniques. For example, in addition to the test techniques/methodology and validation considerations previously described, there are three particular aspects of piloted simulation studies which should be included in the development process for high-angle-of-attack design criteria: (1) the evaluation of candidate criteria, (2) the relationship of these criteria to the design process, and (3) the specification of requirements for demonstrating in flight that the design criteria have been met. The process being used in the development of nose-down pitch control margin design criteria is shown in figure 20. The DMS was used to obtain quantitative results based on the pilot rating scale shown in figure 13. These results were used to develop preliminary design guidelines which are beginning to be applied to specific aircraft. Additional simulation work is being performed to validate the early results, including closed-loop maneuvers. A preliminary set of requirements for demonstrating in flight that the design criteria have been met has been defined. Flight tests of two F-18 aircraft will be performed to validate this process.

Evaluation of Candidate Criteria

Any study to define design criteria should include the evaluation of candidate criteria, beginning with a review of any available literature for existing or proposed criteria or guidelines, in order to determine how much work has been done, how systematic and comprehensive the work was, and how well the results agree with each other. If a reasonable data base of simulation and flight test results exists, sufficient information may be obtained to define a preliminary guideline which can be compared with the simulation results at the completion of the study. The results of such a review of existing guidelines and data bases for nose-down pitch control criteria are contained in reference 18.

An important step in the evaluation of candidate design criteria which relates to the use of pilot rating approaches as well as to the analysis of the simulation results is the establishment of figures of merit to be used in evaluating the aircraft response. As many potential figures of merit as possible should be considered. They can best be compared by characterizing them according to the strength of their relationship to the parameter under design and an appropriate time scale. Figure 21 shows this overall relationship for a number of potential figures of merit which were considered for nose-down pitch control design based on their relationship to pitch control power and the time scale relative to initiation of the pilot command. Those figures of merit on the left side of the scale would be expected to be the more critical ones for design considerations, although the others could also be useful as supplemental or check parameters. For this application it is clear that in the absence of significant angular rates, pitch acceleration ($\dot{q}$) bears a strong relationship to pitch control power because it is directly proportional to static pitching moment coefficient (C_m). The longer time-scale parameters shown

on the right end of the plot have a much weaker association with control power and are more closely associated with airplane performance effects such as thrust and drag. As was shown in figure 18 pitch acceleration was in fact found to be a significant figure of merit, based on the piloted simulation results. The results also showed that the long-term parameters did not correlate as well with pilot opinion of the recoveries from high angles of attack, so this approach to evaluating candidate figures of merit was beneficial.

A final area of consideration for the evaluation of candidate design criteria is the generation of a systematic, comprehensive data base of simulation results, from which the final criteria can be derived. The performance of sufficient runs to ensure the establishment of the pilots' learning curves and a statistically meaningful set of results was discussed previously. For control margin design these results should also incorporate the variation of critical parameters affecting control capability and response. For example, those parameters which were chosen to characterize the static nose-down pitching moment characteristics are illustrated in figure 22 and include: (1) the minimum value of C_m, C_m^*, (2) the angle-of-attack range over which C_m^* occurs, $\Delta\alpha^*$, and (3) the slopes of the pitching moment curve for angles of attack below and above $\Delta\alpha^*$, S1 and S2. Such parameters should be varied individually and systematically for the piloted evaluations. For the nose-down control margin study, 25 separate parametric variations of the nose-down pitching moment capability were evaluated. The range of variations for each characteristic evaluated were based on the characteristics of current aircraft and projected future designs. As a preliminary check on the validity of the initial quantitative analysis of the simulation results, additional maneuvers were performed to verify that the pilot ratings could be predicted for a wide variety of control margin characteristics.

<u>Relationship of Simulation-Derived Criteria to the Design Process</u>

During the early design stages of a new aircraft, the aircraft designer requires guidelines which enable him to design for the desired aircraft performance. Ideally it is best to apply design guidelines as early as possible in the design process such that significant design problems can be identified and design tradeoff studies can be conducted. The format of design guidelines must be easy to apply and yet comprehensive in including the most significant factors which influence the performance. An example of the early application of design guidelines is during preliminary wind-tunnel screening of candidate configurations in which quick assessments of stability levels and control effectiveness are made.

Criteria developed from piloted simulation results can be very useful in developing design guidelines. Usually the intent will be that the aircraft achieve the desired performance demonstrated as satisfactory in the simulator. Very importantly, the designer must have a high level of confidence that use of simulation-derived guidelines will ultimately produce aircraft which meet the original criteria. To achieve this high level of confidence the design guideline must capture the intent of the criteria, including pilot opinion, and ideally should be flight-validated on a variety of aircraft.

A design guideline was developed from nose-down pitch control margin simulation results reported in reference 8. This guideline provided a methodology to determine the minimum value of C_m required at the pinch point (C_m^*) and the shape of the available nose-down pitch response. The basis for this guideline included considerations for pitch acceleration and pitch rate requirements during 1g pushover maneuvers, which were determined to be the most significant figures of merit to use for the design criteria. This guideline is illustrated in figure 23. A methodology was developed to determine design requirements based on the consideration of various maneuvers and motions which involve the significant figures of merit. For nose-down control power the process to select the pitching moment required at each angle of attack, including inertia coupling considerations for rolling maneuvers and motions, is illustrated in figure 24. Three values of C_m are computed based on the maneuvering requirements shown and the largest C_m value is selected.

<u>Flight Test Demonstration Requirements</u>

In the final stages of the design process for a new configuration, flight test is used to demonstrate that the configuration meets design requirements and/or is in compliance with the specifications. Typically a comprehensive set of flight demonstration requirements is outlined prior to the flight test phase and is methodically completed as the flight envelope is expanded.

Piloted simulation is very useful for developing flight demonstration requirements, especially those which are related to simulation-derived design criteria. The specific test techniques and flight conditions can be developed in the simulator in order to determine optimum piloting techniques and the most efficient methods for acquiring the demonstration data. Specific test conditions which are difficult to achieve or assess can be identified prior to flight test. Also, operational constraints on flight demonstrations can be evaluated and alternative demonstration requirements can be developed when required.

Flight demonstration maneuvers which are used to demonstrate design criteria ideally should be closely related to maneuvers used in simulation to develop the criteria. This approach allows the fundamental understanding of the flight dynamics gained from simulation to be applied to flight test and assures that the design methodology is reflected in the maneuver requirements. The flight demonstration should be repeatable and easily accomplished using normal flight testing techniques and not require unusual flight instrumentation for data documentation.

The DMS was used to develop flight demonstration requirements for the nose-down pitch control criteria as previously discussed. The recommended flight maneuvers were closely related to the basic criteria development maneuvers used in simulation. These maneuvers included stabilized 1g pushovers, pushovers during rolling maneuvers, pull-push and zoom climb maneuvers. Successful demonstration of meeting the design criteria included achieving threshold values of pitch acceleration and pitch rate within specified time periods. The DMS was particularly useful for developing the specific test techniques for the flight demonstration. Techniques for achieving 1g stabilized conditions at high angles of attack were evaluated including initial conditions, stabilization criteria, and the impact of engine operating limitations. Also, maneuvers were developed to demonstrate nose-down pitch control during

rolling maneuvers which were very complex and difficult to evaluate. An understanding of the flight mechanics associated with recoveries from zoom climbs was also achieved. In summary, piloted simulation using the DMS proved to be invaluable in developing maneuvers which would safely and efficiently demonstrate compliance with these design requirements. As a final step, these simulation-derived maneuvers will be evaluated in a flight validation program using the F-18 HARV.

5 CONCLUDING REMARKS

Piloted simulation has been an important tool for high-performance aircraft flight-dynamics research at NASA-Langley. It has a major role in the high-angle-of-attack technology development process in the NASA High-Angle-of-Attack Technology Program (HATP), particularly for agility research and design criteria development. The Differential Maneuvering Simulator is the primary facility used for this research, and has been used as an effective research tool to develop the design methodologies required to implement advanced technologies on future aircraft.

Test techniques and methodologies have been developed for the effective use of the simulation capabilities. Certain simulator characteristics are desirable, in order to provide a realistic maneuvering environment. Software requirements, particularly the high-angle-of-attack math modeling of the aerodynamic characteristics, are critical to the successful application of the simulation results. Evaluation maneuvers which are repeatable, easy to execute, and relevant to the research objectives are developed and are usually performed in a progression from the most simple to complex maneuvering and air combat engagements. The most effective use of simulator pilots requires their participation in the research process, particularly for the development of maneuvers and rating approaches and for the identification of appropriate figures of merit for analysis of the results. The data base generated should reflect the establishment of the pilots' learning curves and for design criteria development have statistical significance.

Correlation with full-scale flight results is the primary means of validating the simulation results and approach. The fidelity of the simulation math model can be verified by comparing flight and simulation motions. The utility of evaluation maneuvers and pilot rating approaches used in simulation can be examined in flight. Pilot/vehicle interface considerations and their impact on the simulation results can also be assessed. Flight tests are now underway to validate the approaches used for agility research and design criteria development.

In order to develop design criteria, additional steps are required in the simulation study approach. Candidate design criteria must be carefully evaluated and a systematic, comprehensive data base of simulation results generated. The final criteria developed must be easily applicable to the design process and successfully predict the aircraft performance. Piloted simulation can be used to define flight test demonstration requirements, which can be evaluated in full-scale flight tests.

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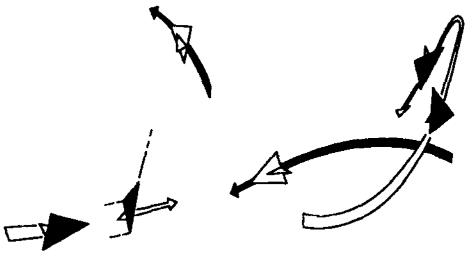

Figure 1. - Illustrations of high-angle-of-attack agility

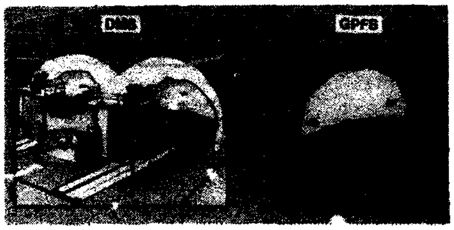

Figure 2. - Simulator facilities used for one-versus-two air combat studies

Figure 3. - Piloted simulation agility research

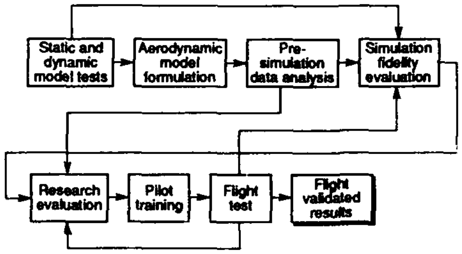

Figure 4. - Approach used for piloted simulation studies

Figure 5. - View of DMS cockpit and visual display

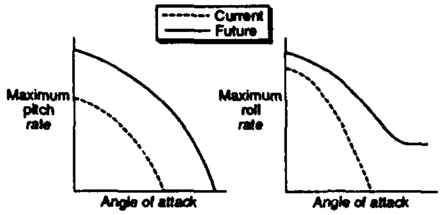

Figure 6. Comparison of current with future pitch and roll rate capability

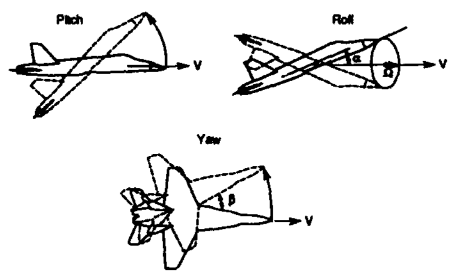

Figure 7. - Characteristic maneuvers

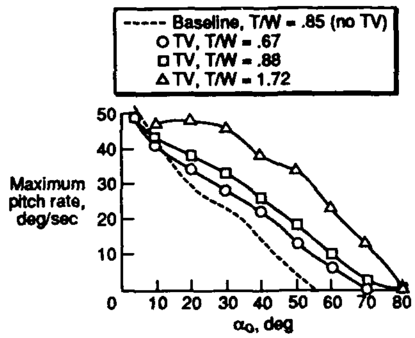

Figure 9. - Maximum pitch rates achieved from 1g trim conditions for various levels of T/W for a configuration with thrust vectoring. h_o = 20,000 ft.

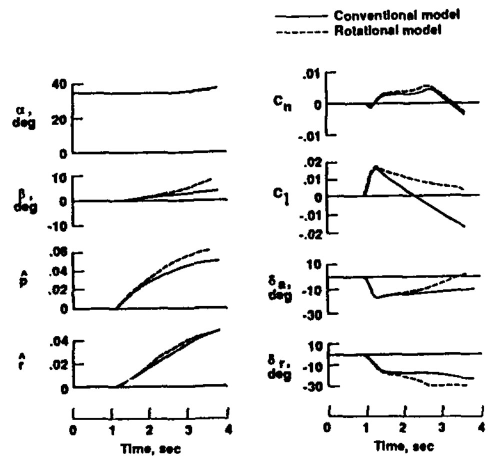

Figure 8. - Time history of large amplitude roll maneuver at $\alpha_o = 35°$ with and without rotary aerodynamics modeled

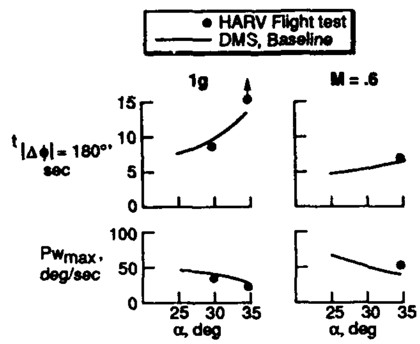

Figure 10. - Comparison of roll maneuvering results for simulation and flight. h_o = 25,000 ft.

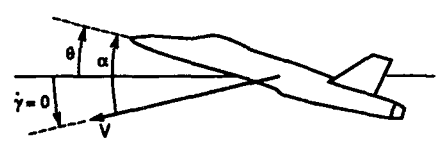

Figure 11. - Stabilized 1g trimmed conditions

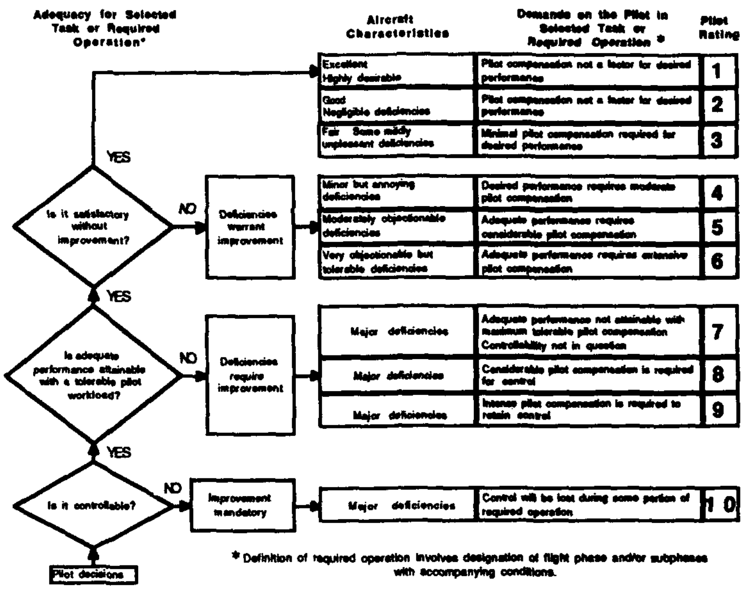

Figure 12.- Cooper-Harper handling qualities rating scale

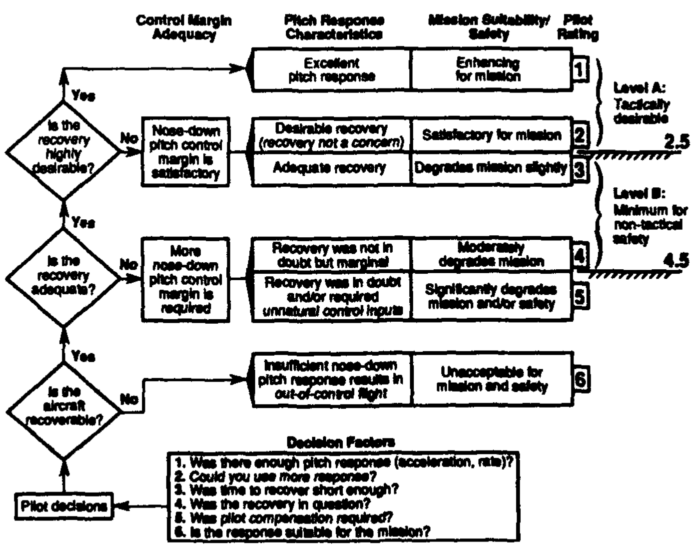

Figure 13. - Pitch recovery rating scale

Use the following questions as a guideline for describing and evaluating each test point.

1. **Describe respone to stick input.**
   a. Pitch response
   b. Accompanying roll/yaw motions
   c. Disorienting motion

2. **Compare this response to other aircraft you have flown.**
   a. Aircraft
   b. Conditions
   c. Similar, better or worse

3. **Give your opinion on the application of this maneuver to combat.**
   a. Characteristics that enhance or degrade combat effectiveness
   b. Describe what you would most like to improve on this response

4. **Determine impact of other influences on your opinion.**
   a. Did recovery time affect your opinion?
   b. Did altitude loss affect your opinion of the recovery?
   c. Were you most concerned about mission safety or mission accomplishment during this maneuver?
   d. Did pilot technique affect results?
   e. What pilot compensation was required to complete maneuver?

Figure 14. - Pilot questionnaire for additional comments

Use the following questions as a guideline for describing the potential tactical applications of each type of maneuver.

1. Based on your experience, would this maneuver be tactically useful for current or future aircraft?

2. What would you like to improve on this maneuver to increase the tactical effectiveness?

3. If this aircraft displayed "excellent" response capability, would this maneuver be tactically useful?

4. Would you desire to have more AOA capability than that demonstrated during this maneuver and why?

5. Describe a tactical situation where you would most likely see this setup and desire to perform this maneuver.

6. What maneuver/s would likely precede and follow this in a tactical situation?

Figure 15. - Pilot questionnaire for evaluation of maneuvers

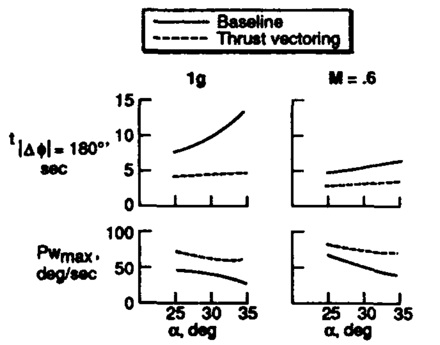

Figure 16. - Roll maneuvering results from simulation evaluation. h_o = 25,000 ft.

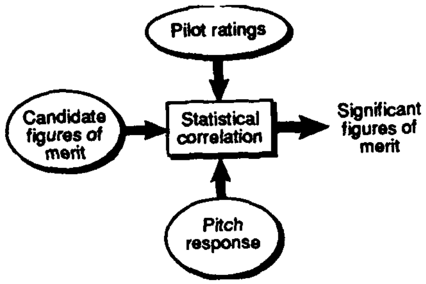

Figure 17. - Approach to data analysis for control margin studies

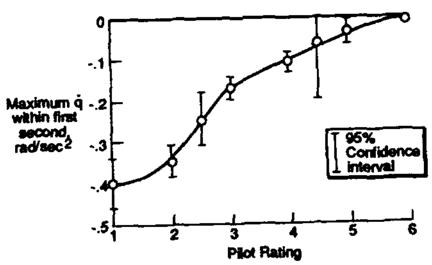

Figure 18. - Variation of maximum q̇ achieved within one second of recovery initiation with pilot rating

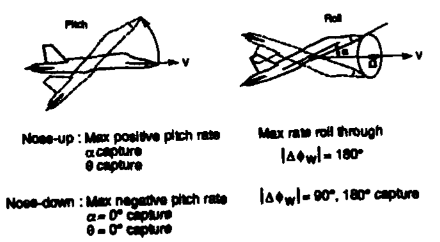

Figure 19. - Candidate maneuvers for agility and control law evaulations

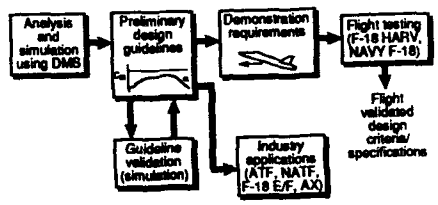

Figure 20. - High-alpha nose-down pitch control margin requirements program

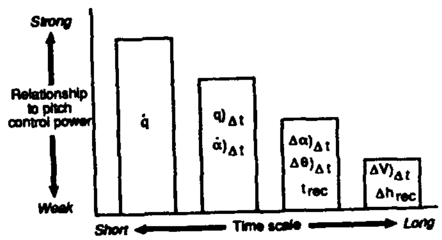

Figure 21. - Candidate figures of merit

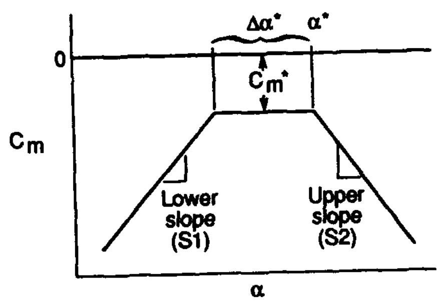

Figure 22. - Parametric variations of nose-down pitching moment used in simulation study

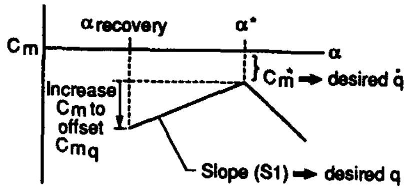

Figure 23. - Illustration of C_m design guidelines for nose-down pitch response

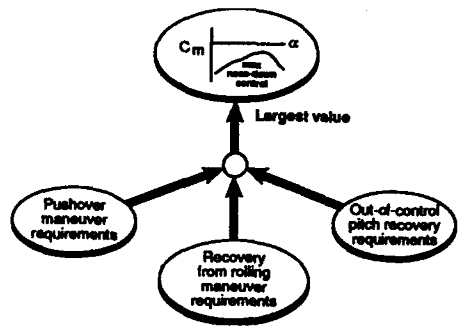

Figure 24. - Illustration of determination of required C_m at each angle of attack

EFFECTIVE CUEING DURING APPROACH AND TOUCHDOWN - COMPARISON WITH FLIGHT

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ABSTRACT

The importance of the various cues provided by flight simulators is a topic for continual debate. Designers of simulators must wrestle with the issue in order to create a sufficient illusion of flight that allows the pilot to carry out his tasks. Hopefully, he becomes stimulated in a similar manner to the real world and behaves accordingly. For training purposes we are then reinforcing behaviour patterns. In research and development simulation we become more confident that problems or deficiencies of pilot/aircraft interaction are identified early. Clearly, if the cueing is identical to the real world, we would expect identical behaviour from the pilot. Simulators invariably fall short of this in many ways. What are considered to be essential cueing requirements are often intuitive, sometimes based on experience and sometimes completely open to individual opinion. A good test of cueing effectiveness is a comparison with flight. The cueing issues for the landing approach and touchdown of fast jets are discussed here and simulator results are compared with flight.

1. INTRODUCTION

A flight trial was carried out by the Royal Aerospace Establishment (RAE, now part of DRA) to examine positional scatter of a Harrier GR3 at touchdown. Slow and Rolling Vertical Landings (RVLS) were carried out on a conventional runway with additional markings representing a narrow airstrip. The objective of the trial was to land within the airstrip as close as possible to a marked area. In parallel with the flight trial a simulator study was run by British Aerospace with the same objective. Results were compared to discover the degree to which flight results could be replicated in the simulator.

The work was then extended to include an additional simulator trial which collected data from landings of the EAP (Experimental Aircraft Programme) demonstrator aircraft on a conventional runway. These were then compared with flight results obtained during routine flight trials of the EAP.

The simulators at British Aerospace Military Aircraft, Warton, England were used for the experiments. These are used extensively for Research and Development programmes in support of aircraft projects. The simulators also have their own development programmes which introduce new technology as appropriate in order to increase their cost effectiveness.

The experiments were therefore carried out using the standards of simulator cueing currently in use. As such, the emphasis of the work was in evaluating a particular level of overall simulator cueing rather than experimentally proving the value of any one cue over another.

In the following section, simulator cue is discussed in general. This leads on the philosophy behind the cueing used for the experiments.

2. SIMULATOR CUEING REALISM

The objective of the cueing system was to achieve similar results between simulator and flight during landing approach and touchdown. Clearly this is largely a motor skills task and relies heavily on providing the simulator pilot with the same stimulation as during flight. If he regards the simulator as realistic he should achieve similar touchdown performance to flight. If he achieves this performance using similar control methods and activity, then the simulation can be regarded as more realistic still. Degrees of realism are of course subjective and can be difficult to quantify.

For some elements of the cueing system, realism is achieved through accuracy. This is not always possible and the situation can arise where the two requirements actually conflict.

The compromise between realism and accuracy is discussed by A G Barnes in Ref 1 with regard to classifying simulators. The same considerations can, however, be applied to the component parts of the overall simulator cueing system. Some of these provide primary cues whilst others contribute towards a primary cue.

2.1 Control Stick Characteristics

It is relatively straightforward to provide inceptors with accurate feel characteristics. For these experiments the aircraft stick units were replicated in the simulators with sufficient accuracy for the pilots to recognise the similarity. The EAP simulator was fitted with the most accurate replica. This high degree of accuracy can be regarded as implying a corresponding high degree of realism. That is, we can regard these inceptors as being both accurate and realistic.

2.2 Motion

It is generally accepted that motion cues are important for high gain simulator tasks such as the control of low stability vehicles (Ref 2). The aircraft under consideration in the experiments reported here were well stabilised and controllable. For this reason a fixed base simulator was used. Vestibular motion cues were therefore absent and in this respect the simulator was completely inaccurate. Therefore, the only method by which any realistic sensation of motion could then be applied was through the visual system.

2.3 Audio

The predominant audio cue represented the engine as heard from outside the aircraft. The provision of a touchdown sound gave a positive indication of ground contact. Both of these effects were not accurate and did not represent what can be heard inside a cockpit and flying helmet. During flight, engine condition can be sensed through the airframe and the cockpit air conditioning system.

The moment of touchdown can of course be felt by the pilot. Nevertheless, the realism of the simulation was increased by means of these inaccurate cues.

2.4 Visual

The visual scene was undoubtedly the predominant cue in these experiments. The various parameters which define the accuracy of the visual system are manifold. Some of the more significant ones are considered here. In some cases well established guidelines can be called upon to decide on appropriate values.

Take, for example, the transport delay between control stick movement and apparent displacement of the visual scene. Figure 1 shows the results of several experiments (Ref 5) where a delay was added to the stick forward path. Beyond about 110ms Pilot Ratings are seen to be degraded. This can be regarded as saying that realism (i.e. no change in pilot rating) is maintained with delays up to this value. The measured delay on the simulators used for the approach experiments was a maximum of 110ms, i.e. they can be regarded as sufficiently realistic in this respect.

Complex and accurate models of the aircraft dynamics and flight control systems were used. In order to minimise the transport delays it is important to achieve a high solution rate within the computing system. A typical iteration rate for aircraft dynamics used in this experiment was about 350Hz.

A Cathode Ray Tube (CRT) video projection system was used to display the outside world image. The brightness and resolution of the resulting image were significantly below that of the real world.

	Real World	Simulator
Brightness ft lamberts	> 10,000	1
Resolution arc min/olp	< 1	8

However, the field of view of 180° wide by 48° high was perfectly adequate for representing this task and in this respect could be considered both accurate and realistic.

The way Computer Image Generators operate on their database in terms of perspective and occultation processes can be regarded as accurate and realistic. This is discussed later in more detail.

The size and complexity of the databases which can be processed by modern visual systems is, however, limited. The ESIG-500 used for the experiments can display around 500 polygons per channel and is considered to have mid-range performance. A few thousand polygons is the upper limit of today's technology. In theory, an electronically generated scene could contain a separate polygon for each displayable pixel. To achieve this, the system would need a capacity of over one million polygons.

Given such a restriction in the accuracy of scene content, there is the potential for a similar shortfall in realism. It is essential therefore that visual cueing is applied as effectively as possible in order to maximise realism.

A.G. Parfitt (Ref 3) offers a similar argument with regard to training simulators which use low-cost image generators. His general conclusions, however, apply equally for research simulators such as these using medium cost visuals. He refers in particular to matching cueing to the task and avoiding attempts to duplicate all aspects of the real world. That is achieving realism without accuracy. These principles appear sound and are borne in mind in the following discussion.

3. VISUAL SCENE CONTENT

The requirements for visual space perception important to the landing task are discussed by A Buffet (Ref 4) where the strongest cues in static images are considered to be size constancy,

interposition, linear perspective, and aerial effects. Those important for dynamic images are movement parallax and retinal disparity.

Size constancy is the effect of distant objects appearing smaller than closer objects of the same size. Knowing the absolute size of the object thus allows the viewer to appreciate its range. The first characteristic of the visual scene should therefore be to include objects of familiar size.

The effect of a near object obscuring a far one is known as interposition. Both this effect and linear perspective are automatically produced by the transformation and occulting processes of most computer image generation systems. This effect acts both on the polygons in the scene as well as on the texture patterns within those polygons. However, in order to maximise this effect, objects should be positioned within the scene so that during the landing approach object groups 'unfold'. Individual objects should also be fairly close to the flight path. Liberal use of high contrast texture should also encourage the effect.

Movement parallax is the effect whereby distant objects have a smaller apparent relative velocity than closer ones. It is the dynamic equivalent of interposition. The same guidelines as for interposition and perspective effects should be followed.

Included in aerial effects are shading and shadowing. The effect of sun angle on the objects is to increase the contrast between similar coloured surfaces because of their different incidences to the light source. Maximising this effect clearly adds to the 3-D impression of the scene.

Another effect of this is the creation of ground shadows. These can be thought of as additional polygons attached to a given object and related geometrically to it. Hence they provide additional information about the scene. An added effect is that smaller objects, particularly those with a small 'footprint' are less likely to appear detached or 'floating' above the ground. One of the objects which subjectively appear to benefit are trees.

Retinal disparity is the perception of 3D due to the separation of the eyes. The simulator configuration used for the experiment was based on the projection of real images onto a single curvature screen 3.5 metres from the pilot by means of CRT projectors. The effect of retinal disparity was not represented by the simulator, but with the limited display resolution even a binocular display would only show retinal disparity of objects at visual ranges of less than 50 metres.

Visual acuity and therefore the perceivable resolution is known to fall off as angle from the fovea increases (Figure 2). Towards the limits of the eye's field of view only large sudden object movement can be detected. To take maximum advantage of the effect we firstly require a field of view which matches that of the eye. It is reasonable to assume that during the landing task, the pilot fixes his gaze more or less at his intended landing point directly ahead. The field of view in the simulator of ±90° about this point should therefore suffice. Secondly, in order to cue the pilot for roll attitude and linear velocity at these large angles-off, large objects of high contrast should be included in the proximity of the runway.

All of the effects described here were considered to benefit from the maximum contrast which could be produced from the visual system.

In defining this need for high contrast texture areas over large parts of the scene in order to meet the above requirements, the illusion of vection is also being encouraged - ie. the illusion that the pilot of the simulator is actually moving as a result of being presented with a moving outside world scene. Vection or 'picture flow' is widely recognised as essential in cueing the pilot for low flying. This is clearly an important effect if flare manoeuvres are to compare well with flight. When using high contrast textures, care must be taken to ensure that any repeating pattern does not cause stroboscopic effects when viewed at speed, otherwise the vection effect is reduced or lost completely. Tiles within a runway pattern are an example of an area for caution.

Based on the above discussions, the following 'ground rules' summarise the characteristics to be aimed for:

1. High contrast between features in the scene.
2. Many textured surfaces painted with high frequency texture.
3. Use of sun shading and shadows.
4. Large objects close to the line of flight.
5. Groups of objects close to the line of flight.
6. Objects to be of familiar size.

For operational reasons, two standards of visual image database were constructed for the simulator experiments each incorporating some or all of these guidelines.

4. SIMULATOR EXPERIMENTS AND FLIGHT TRIALS

The simulator configuration was similar for both experiments. Some of the key elements have already been discussed with regard to their cueing contribution. The specific differences between the simulators are discussed below.

4.1 Harrier Simulation

The simulator was fixed base for the experiment. A generic cockpit was fitted with a feel unit which gave similar forces and travels for the approach phase as in the Harrier aircraft. A Head-Up Display (HUD) in the cockpit gave 1:1 climb-dive information but no landing guidance and no velocity vector.

Three windows of Evans and Sutherland ESIG-500 were projected onto a dome to cover 180° wide by 48° high field-of-view. The vertical arrangement was 15 deg up and 33 deg down from the horizontal. Continuity of the image was ensured by means of a window blending system developed in-house. A visual database was constructed based on the DRA Bedford airfield where the flight trials were conducted. Within the runway an additional narrow strip of 8 x 750 metres was marked. The marks were positioned identically to those in the flight trial except for an additional touchdown marker. All markings were made at the maximum contrast ratio available. In this database, buildings were not placed abnormally close to the runway. Figure 3 shows the scene with the hangars and other buildings some distance away.

Landing guidance was provided by PAPIs (Precision Approach Path Indicators) set at either 3 deg or 5 deg depending upon the type of approach. A total of 270 slow landings with a nominal 3 deg glideslope were flown at a constant speed of about 120kts. In addition 250 Rolling-Vertical landings (RVLs) starting at 90kts and touching down at about 60kts were flown at a final nominal glideslope of 5 deg.

A range of simulated turbulence (based on Dryden spectra) from zero to 2m/s rms was applied during the experiment. Various crosswind conditions up to 15kts were also applied.

Four Harrier test pilots took part in the experiment. They were briefed to carry out unflared landings as close as possible to the touchdown marker.

4.2 Harrier Flight Trials

The flight trials were carried out by RAE (now part of DRA) at the Bedford site. An RAF Harrier GR3 aircraft was made available with approach guidance aids and ground instrumentation provided by RAE. The runway markings have already been discussed. As in the simulator experiment PAPIs were provided as landing guidance. The Harrier was fitted with a 5:1 climb-dive HUD but as in the simulator, no velocity vector.

The same four pilots took part in the flight trials and again, they were briefed to fly unflared landings. The total number of slow landings
was 121. RVLs totalled 95.

4.3 Harrier Comparison

The results of the RAE flight trials were analysed by BAe. The scatter comparisons for RVLs and slow landings are plotted separately in Figures 4 and 5. Means and standard deviations are plotted for the flight trials in total. These included the same range of crosswinds as in the simulator. Although no measurements were taken at the time it was considered that the turbulence levels during the flight trials were not high. With this in mind, the simulator results for RVLs are plotted both in total and for zero turbulence and crosswinds.

The scatter in both cases shows a remarkable similarity when the zero crosswind/turbulence values are compared with flight. This scatter increases however when turbulence and crosswinds are applied, but for the reasons stated earlier, some of the simulated turbulence was probably too severe.

The slow landings compared in Figure 5 again show very good correlation. A noticeable factor in both types of landing is the displacement of the mean values between flight and simulation. The reason for this is unclear, although a tendency to flare the aircraft which was not seen in the simulator may have pushed the mean point further down the strip. The measured sinkrates from flight were consistent with this theory since on average they were less than those seen on the simulator.

4.4 EAP Simulation

The tendency to flare during the Harrier flight trials and not in the simulator meant that touchdown sinkrates could not be meaningfully compared. For this reason, the EAP simulation experiment was conducted to gather data more or less exclusively on sinkrates. Again the emphasis was placed on cueing mainly through the visual system.

The simulator arrangement was similar in that a fixed based cockpit was used, with a mechanical replica of the EAP control stick. A projected visual arrangement similar to the Harrier trial was used, driven by the same ESIG-500 visual generator. In this case, however, the HUD was projected onto the same focal plane as the outside world rather than using a cockpit unit. This arrangement was designed for research into wide field-of-view HUDs. Figure 6 shows the simulator in use.

For the experiment, the EAP 1:1 HUD format was used. As the aircraft descended below 250ft altitude this was simplified to contain only airspeed, altitude and angle of attack. This ensured that visual cueing played a major part in determining touchdown performance rather than a reliance on HUD information.

Since the flare manoeuvre was probably more important in this experiment, the opportunity was taken to construct a visual database using more of the 'guidelines' discussed earlier. Figure 7 shows a view during the approach. Groups of familiar sized buildings including hangars and control towers have been positioned alongside the threshold but much closer than in any real airfield. Close to the line of flight are other familiar objects such as electricity pylons, trees, farm buildings, barns, grain silos, etc. Clearly there is scope for the size of any of these objects to be misinterpreted in isolation. However, the intention was to include a number of them together so that they could be visually compared and hopefully reinforce one another's cues. High contrast texture was again used liberally throughout the scene as well as shadows from trees and pylons.

No landing guidance was provided and a total of 30 landings were carried out. The brief was for the pilot to achieve similar sinkrates as in routine test flying, with less concern for touchdown scatter.

All simulator runs were carried out in still air. An EAP test pilot took part in the experiment, since he also produced the flight data used in comparison.

4.5 EAP Flight Trials

The same pilot had previously flown 28 test flights with the same standard of aircraft as used in the simulation. The sinkrates were extracted from routine flights made from BAe's Warton airfield. Consequently the landings were subject to a wide range of turbulence and crosswind conditions.

4.6 EAP Comparison

The mean values for simulation and flight differed by about 1f/s (3.5f/s simulated, 4.5f/s flight). The histograms shown in Figure 8 show the peak for flight results to be more distinct than simulation results. The tendency for lower sinkrates to be produced on the simulator may be due to the still air conditions used. In general terms the results are close and encouraging since it is often the case for simulator sinkrates to be larger than flight. The samples (30 simulator, 28 flight) are not large but clear trends can be seen.

A comparison of typical stick activity used during the landings is shown in Figure 9. Again the comparison is between still air (simulator) and some turbulence (flight). The frequency and amplitude of the stick time histories are somewhat different, showing that a different control strategy is being used in the simulator. There is, however, in each case a point where stick activity increases. Around 5-7 seconds before the touchdown, the flare is initiated and the level of activity increases significantly in both simulator and flight. This provides further confidence in the effectiveness of the overall cueing.

5. PILOT COMMENTS

In general, the simulators and the cueing they provided were liked by the subject pilots. The resolution of the outside world display was good for showing the detailed runway texture in the flare below about 30ft altitude. An increase in resolution however, would also have helped during initiation of the flare. The other runway markings, nevertheless, provided good flare cueing - particularly the piano keys and centrelines. The remaining features in the visual scene, e.g. buildings, shadows, etc, were all thought to be effective earlier in the approach.

6. CONCLUSIONS

An opportunity has been taken to compare simulation and flight results during landing approach and touchdown for Harrier and EAP aircraft.

The simulator cueing requirements were considered in terms of their accuracy and realism. In addition to accurate cueing through control feel simulation and aircraft dynamics modelling, supplementary audio cues were also provided.

The visual scene played a key part in cueing the pilot. Although the visual cues could not be considered accurate, they were optimised with the intention of inducing realistic behaviour in the pilot. The effectiveness of the overall cueing was checked by comparing touchdown scatter and sinkrate between simulator and flight test. In general, the degree of correlation confirmed the suitability of this configuration of simulator and the characteristics of its visual system for the landing approach and touchdown task.

Reference 1 The Compromise Between Accuracy and Realism in Flight Simulation. A G BARNES, AIAA Flight Simulation Technologies Conference. August 1991

Reference 2 The Need for Platform Motion in Modern Piloted Flight Training Simulators. J R HALL, RAE Technical Memo FM35, Oct 1989.

Reference 3 Visual Scene Content and Training A G PARFITT, Royal Aeronautical Society Conference "Low Cost Visual Systems". November 1988

Reference 4 Visual Cueing Requirements in Flight Simulation. A R BUFFET

Reference 5 Simulation as a Fighter Design Tool. J R LOCKENOUR, AGARD LS153 June 1986.

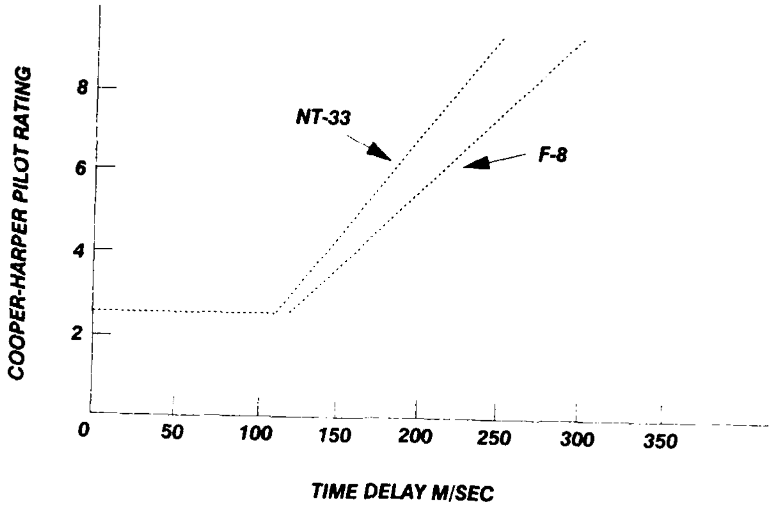

FIG. 1 EFFECT OF TIME DELAYS ON PILOT RATING FOR LANDING APPROACH

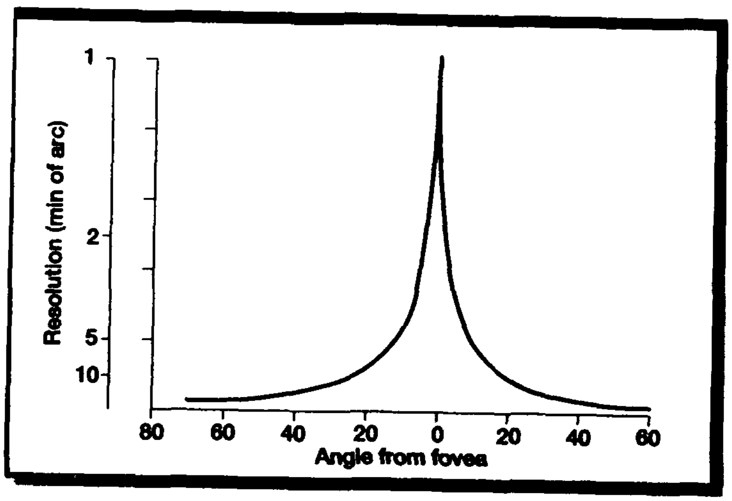

FIG. 2 LATERAL RESOLUTION OF THE EYE

FIG. 3 BEDFORD AIRFIELD DATABASE FOR HARRIER EXPERIMENT

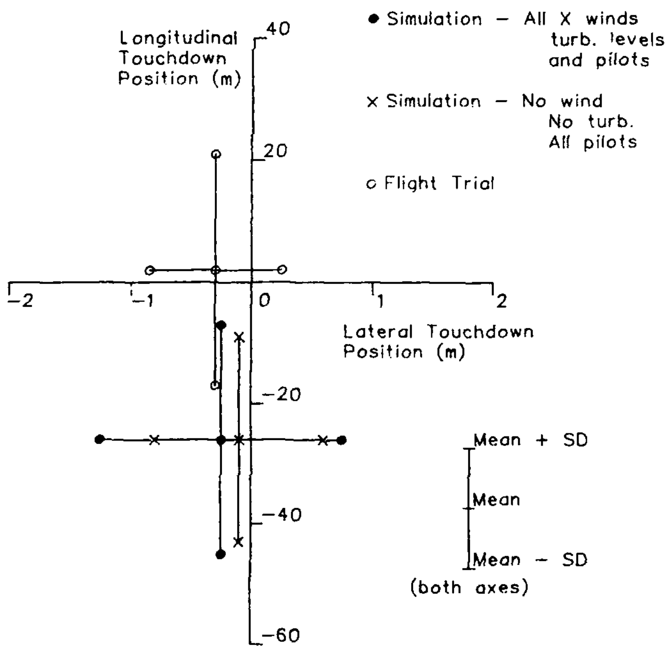

FIG. 4 COMPARISON WITH FLIGHT - TOUCHDOWN ACCURACY HARRIER RVLS

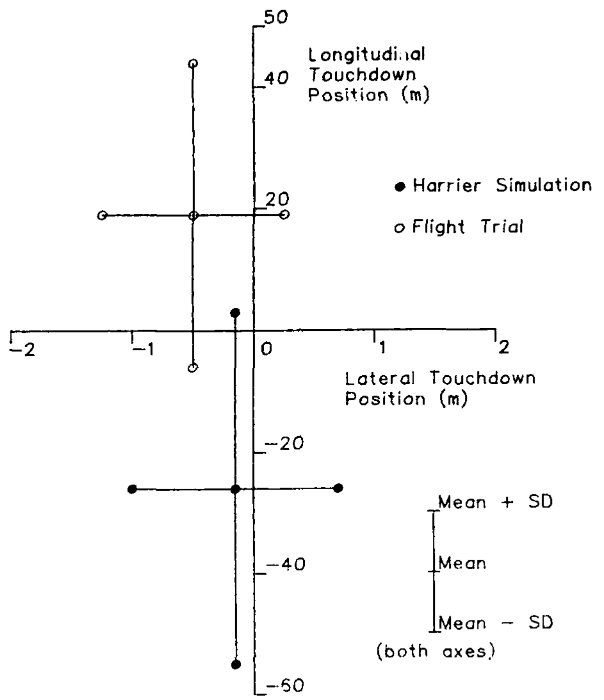

FIG. 5 COMPARISON WITH FLIGHT - TOUCHDOWN ACCURACY HARRIER SLOW LANDINGS

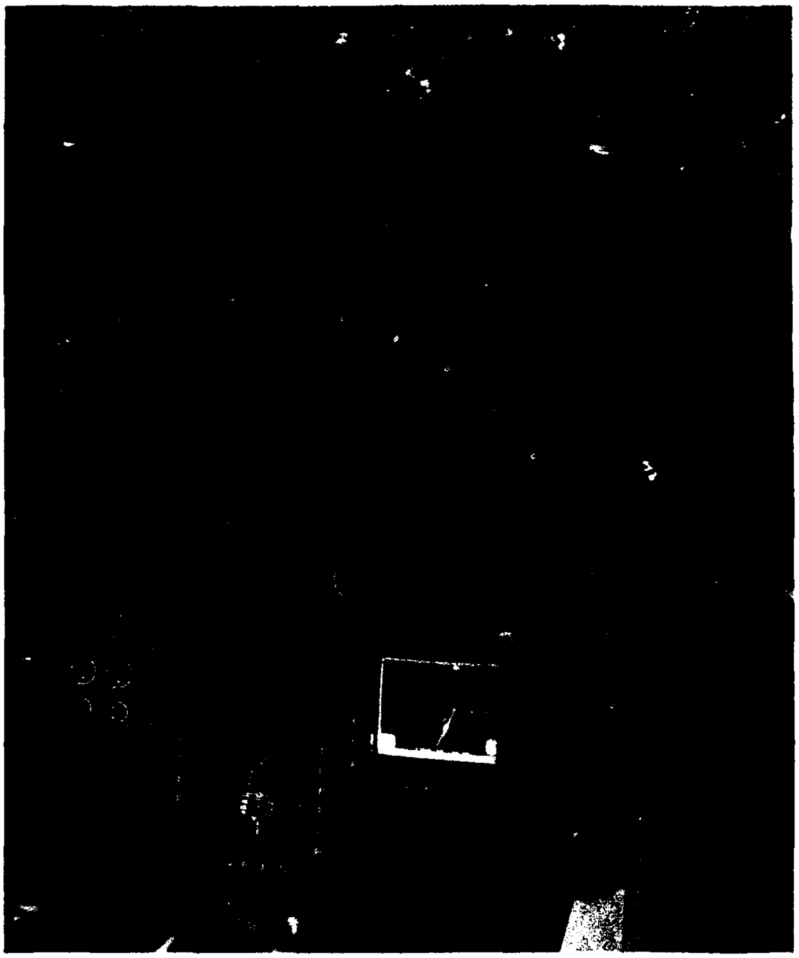

FIG. 6 EAP SIMULATOR

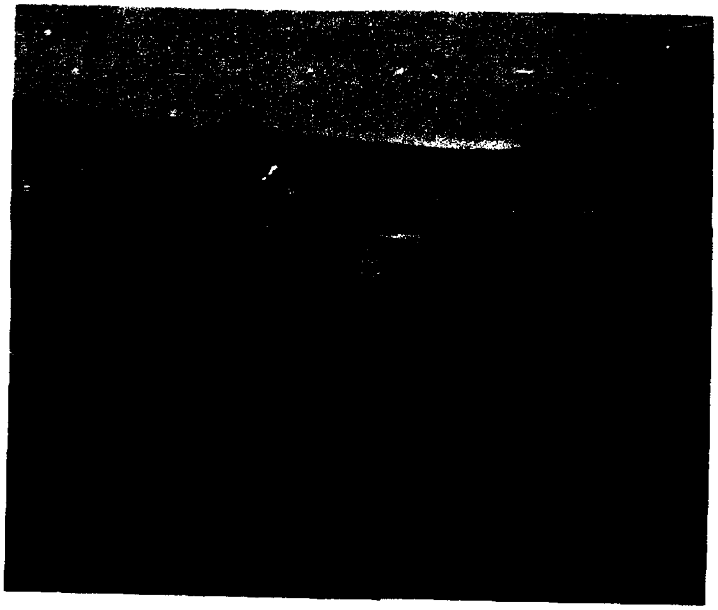

FIG. 7 VISUAL DATABASE USED FOR EAP EXPERIMENT

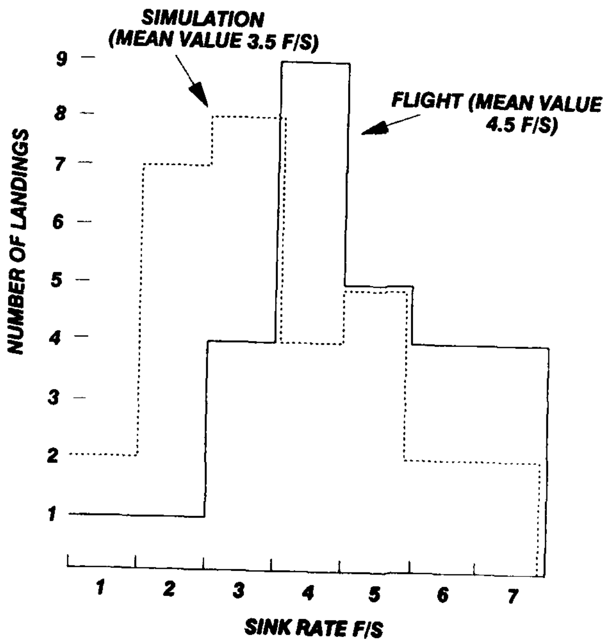

FIG. 8 HISTOGRAMS OF SINK RATE AT TOUCHDOWN FOR EAP. SIMULATOR AND AIRCRAFT FLOWN BY SAME PILOT.

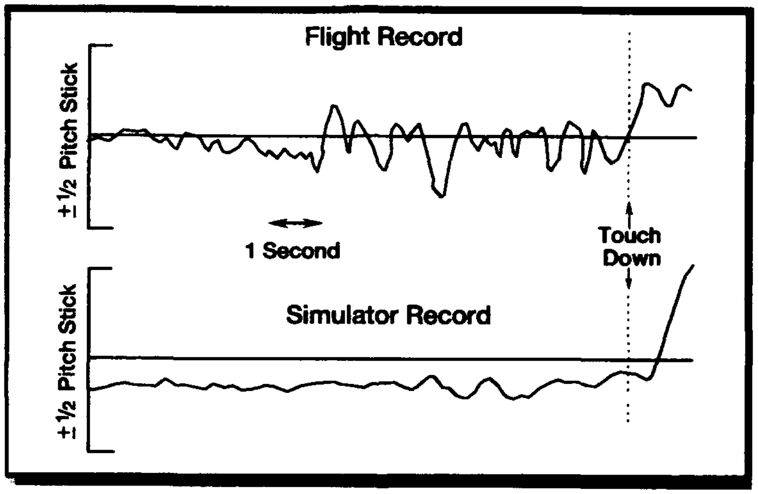

FIG. 9 PITCH STICK ACTIVITY PRIOR TO TOUCHDOWN

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14. Abstract

The ability of piloted simulators to represent military and civil aviation operational tasks with ever-increasing levels of fidelity is leading to a steady growth in their use for all areas of aviation from new concept studies, through support for development and flight clearance, to training aircrew for complex missions. In all applications of simulation the essential question is "What level of confidence do I have in this simulator's capabilities to represent the tasks I am going to perform?" This Symposium has brought together papers presenting a variety of experience of the effectiveness of simulation for many of the key areas of applications.

Sessions focused on:

- the use of simulation in aircraft development programmes, including some of the issues raised by the use of simulation as part of flight clearance activities;
- the use of simulation in developing piloting skills;
- the use and potential of simulation in full mission training for military rôles;
- the effectiveness of simulation for a variety of research tasks, including developing flying qualities criteria and exploring new concepts.

The aim was to give attendees a view of the many contributions made by flight simulators, a change to update their knowledge of the effectiveness of simulation for a wide range of tasks, and a glimpse of the future potential of simulation.

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